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RANDOM ACCESS STRATEGIES STANDARD FRIENDLY WITH IEEE 802.15.4

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Abstract

The IEEE 802.15.4 protocol is one of the solutions available on the market for LPWAN, which offers several physical layer implementations, from which we have chosen to study the physical channel based on Chirp Spread Spectrum (CSS). One of the main limiting factors for when multiple users share the same network and resources is the multi-access interference (MAI). Random Access Protocols and interference cancellation (IC) policies have been proven to counteract this problem. Furthermore, the introduction of Forward Error Correction (FEC) codes, is another method employed to enhance the performance of a communications system. Convolutional Codes are extremely useful for real-time communications that require continuous data transmission, as the encoding and decoding can be done continuously too. The decoder employs the Viterbi algorithm, which is based on maximum likelihood (ML) decoding with previous knowledge of the convolutional encoder operation, either with Hard or Soft decision decoding, which directly has repercussions on the overall performance of the system.

Therefore, the aim of this project is first to evaluate the performance of the IEEE 802.15.4 standard under different channel scenarios. Then evaluate the difference in performance when applying SIC techniques in the system with the objective of enhancing the results. Lastly, we will analyze the performance results of including convolutional coding and Viterbi decoding into our implemented system with different levels of modifications.

Keywords: Internet of Things (IoT); Low Power Wide Area (LPWA); IEEE Standard 802.15.4; Chirp Spread Spectrum (CSS); Successive Iterative Cancellation (SIC); Convolutional Coding; Viterbi Algorithm; Soft and Hard Decision Decoding

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Contents

List of Figures

List of Tables

Introduction

This thesis is the result of half a year's work on the Department of Signal Theory and Communications under the framework of evaluating the performance of Random Access strategies applied to a standardized communications protocol for Low Power Wide Area Networks (LWPAN) IEEE 802.15.4. Moreover, Successive Iteration Techniques (SIC) have been implemented as a performance enhancing method. Furthermore, we have studied and analyzed the performance of including Convolutional Coding and Viterbi Decoding techniques into this system, creating a Standard friendly system implementation and a non-Standard friendly scenario.

This document provides a detailed description of the most important contributions achieved in the past few months. The initial stage of the research, involved an in-depth study on the foundations and state of the art of M2M communications, SIC techniques and coding and decoding methodologies. Followed by the practical or implementation stage, which consists on the creation of different scenarios and the analysis of the obtained results.

1.1 Statement of Purpose

The new Internet of Things (IoT) paradigm and machine-to-machine (M2M) communications are foreseen to arise as new technologies in the next following years. As a result, they are forcing the development of new communication networks and protocols to be able to adapt to the radically different requirements compared to traditional communication systems.

Both services require connectivity over a potential population of users over a shared communication environment at a very low cost, featuring several low forms of data traffic and very long life times of the devices due to long sleep periods, which in turn demand adaptability to different delays and low energy consumption.

All of the previous communications demands are covered by Low Power Wide Area Networks (LPWAN). Several solutions are already on the market, both proprietary or standardized. However, we have chosen to focus on the standardized IEEE 802.15.4 protocol, after reviewing all the options available on the market. This standard was chosen because it was not a proprietary technology and because it offers several physical channel implementations from which to choose from.

Moreover, between those we have chosen to implement and analyze the performance of applying a physical channel based on Chirp Spread Spectrum (CSS), as it is a highly regarded and employed solution in the market.

Random Access Protocols have been found to be a key element of communication systems in these LPWAN scenarios. However, inter-user interference constitutes the main limiting factor to network performance under these protocols. In this respect, interference cancellation (IC) policies have proved to be an invaluable tool in order to counteract this problem.

Thereafter, we will implement these techniques, specifically Successive Interference Cancellation (SIC) techniques to evaluate the performance of the system before and after to observe the variation.

Furthermore, error control coding, is another method employed to achieve minimum error-free communication between the transmitter and receiver under a noisy channel. There are mainly two types of error correcting codes, being Forward Error Correction (FEC) codes the most relevant, as it detects and corrects the errors at the receiver without requiring the transmitter to resend the original data signal.

From these category, Convolutional Codes are extremely useful for continuous data transmission, thus in real-time communications as encoding and decoding can be done continuously too. The best and most common approach to decode these types of codes is the Viterbi decoding algorithm, which is based on maximum likelihood (ML) decoding with previous knowledge of the convolutional encoder operation.

For this reason, we are going to implement this type of encoder and decoder into our system to analyze how the resulting overall performance varies due to these two blocks.

Therefore, the aim of this project is to evaluate the performance of the IEEE 802.15.4 standard under different channel scenarios. Moreover, we will evaluate the difference in performance when applying SIC techniques in the system with the objective of enhancing the results. Furthermore, we will create two scenarios including convolutional coding and Viterbi decoding into our implemented system, both with different levels of modifications, in order to analyze the performance results.

1.2 Project Outline

This project will then follow the previous layout. It will be divided in three parts.

First of all, the IEEE 802.15.4 Standard has been thoroughly studied. Due to the amount of different physical channels defined in the standard, a state of the art and a study into each technique has been conducted, in order to be able to select one. The implementation of this standard has been based on the physical channel modelled for Chirp Spread Spectrum (CSS) as described in the standard. Afterwards, we have created different scenarios for which we have evaluated the performance. We have defined single user and multi-user schemes under different conditions for the Standard to obtain the first set of results.

Second, we have studied and implemented into our Standard system novel Successive Interference Cancellation Techniques to evaluate the enhancement in performance for multi-user scenarios. Again, we have created different scenarios with the added inclusion of SIC techniques into the system, for which we have evaluated the performance. We have defined single user and multi-user schemes under different conditions for the Standard to obtain the first set of results.

Third and last, we have introduced coding and decoding techniques into our Standard system, specifically an error correction scheme based on Convolutional codes and Viterbi decoding, to identify and show the potential a simple error correcting coding scheme can have on the overall performance of a system. In this part, we have defined two different scenarios, one standard friendly, for which we don't modify the already implemented system, and another scenario non-standard friendly, which consists of excluding some parts of the standard and implementing coding and decoding blocks. Afterwards, similarly to the previous parts, we have defined single user and multi-user schemes under different conditions for both of these scenarios, and analyzed the obtained performance results.

A thorough analysis into each set of results has been made and we have arrived to several conclusions. Additionally, we propose several further development and future investigation paths in line with this project.

State of the Art

Next generation 5G of communications systems is promising a plethora of new communications paradigms on top of supporting conventional voice and data services [1]. In between those new proposed applications we encounter with Internet of Things (IoT) and Machine-to-Machine (M2M) services, which are gaining more and more attention.

IoT can be defined as a global network infrastructure where its devices are all interconnected an exchanging data without the need for human interaction. These devices then come under the scope of M2M communications services, where the devices exchange data automatically without intermediaries.

However, the integration of these devices or smart objects into the conventional Internet introduces several new challenges as they have characteristic and different service requirements. These devices need to support several forms of data traffic and different delays. Usually, they are designed to be low cost and with low energy consumption thus having limited power. Furthermore, these devices, contrary to conventional cellular technology, transmit short packets regularly, thus having short constant changes from active and sleep cycles.

As a result, we have a considerable amount of devices interconnected to the internet with limited resources and distinguishable characteristics compared to conventional cellular standards [2,3].

These requirements and specifications have been gathered under the scope of Low Power Wide Area (LPWA) Technologies. LPWA networks aim to achieve all the previously mentioned and key characteristics required to fulfill the IoT paradigm. For this reason, these technologies are being currently studied and several solutions both standard and proprietary have been developed.

We can distinguish two categories of technologies based on the connectivity method used to offer wide area coverage. First, operating on license spectrum 3GPP standardized cellular IoT technology which is evolving LTE towards narrow-band IoT (NB-IoT). These cellular technologies, such as GSM, WCDMA, LTE and 5G, target high-quality mobile communications voice and data services. However, due to the demand for the evolution into LPWAN, they have evolved and begun adapting and creating new standards to service this new paradigm, such as 3GPP has standardized the enhanced MTC (eMTC), narrowband IoT (NB-IoT), and extended coverage GSM for IoT (EC-GSMIoT) [4, 5]. Second, new proprietary radio techniques, such as LoRa and Sigfox, operating under the unliscensed industrial, scientific and medical (ISM) radio bands, that have been developed for M2M communications services and applications[6,7].

In the following figures we show the different developed LPWA standards and proprietary technologies currently in the market.

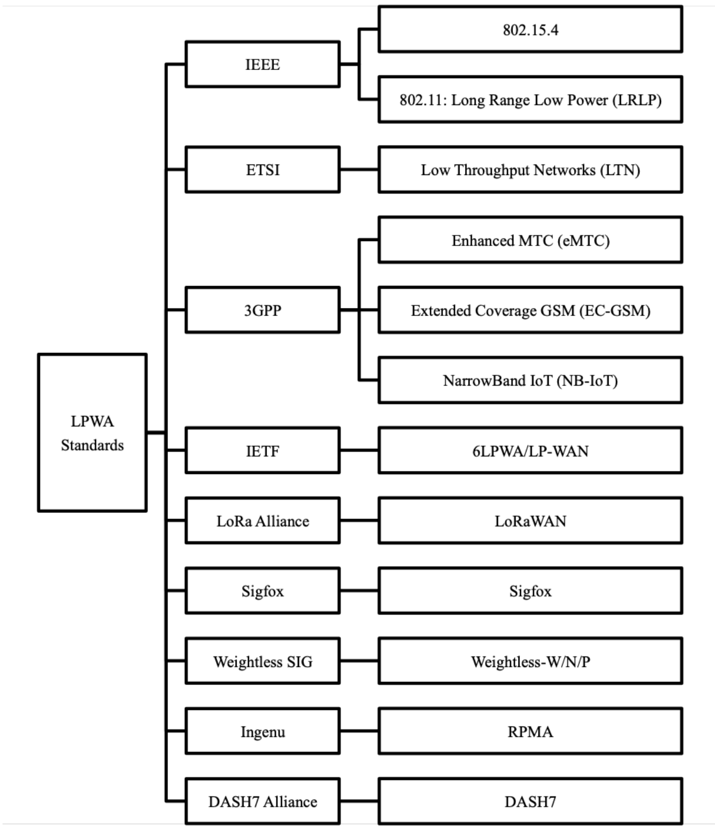

Figure 1: LPWA Standards

As these techniques have been solely developed for the IoT paradigm, several commonalities can be found between them regarding the different techniques employed to adapt and realize each characteristic requirement. However, as we can see from the following table, all these standards and technologies also have radically different types of techniques to achieve all the previously mentioned requirements. This variety of approaches provides the user with additional diversity and thus beneficial when they are deployed as they share and compete in the same portion of the spectrum [7].

In the next table we have summarized their main characteristics, where we can appreciate their differences and similarities.

	LoRaWAN	Sigfox	Ingenu	Weightless	DASH7	IEEE 802.15.4	NB-IoT
Topology	Star of starts	Star	Star, Tree	Star	Star, Tree	Star, Mesh,	Star
Range	5-15km	10-50km	15km	2-5km	0-5km	5km	15km
Modulation	CSS	UNB, DBPSK(UL), GFSK(DL)	RPMA-DSSS(UL), CDMA(UL)	16-QAM, BPSK, QPSK, DBPSK, UNB DBPSK, GMSK	GFSK	DSSS, FSK, OFDMA, OQPSK	QPSK
MAC	Unslotted ALOHA	Unslotted ALOHA	CDMA-like	FDMA/TDMA or slotted ALOHA	CSMA/CA	CSMA/CA	FDMA /OFDMA
Band	Sub-1GHz ISM	Sub-1GHz ISM	ISM 2.4GHz	Sub-1GHz ISM	Sub-1GHz ISM	Sub-1GHz ISM and 2.4GHz	Liscensed 7-900MHz

Table 1: Characteristics of LoRaWAN, SigFox, Ingenu, Weightless, DASH7, IEEE 802.15.4, NB-IoT [2,7-15]

As we can observe in the previous table, several technologies have several commonalities between them, as they have been all developed to achieve the same requirements for unlicensed LPWA. For this reason, we are going to summarize the common principal techniques employed to achieve the different characteristics that define this new paradigm.

First of all, to provide wide area coverage and achieve long range LPWA technologies operate in unlicensed ISM radio bands 169, 433, 868/915 MHz, and 2.4 GHz depending on the region of operation. From table 1 we can appreciate the different unlicensed bands used by the different technologies. SigFox and LoRa employ the sub-1GHz band, which has been proven to help achieve maximum coverage [4].

However, technologies such as Weightless, Ingenu and Zigbee, operate in the 2.4GHz band, which is more congested than the sub-1GHz band as it is employed by popular wireless technologies, Wi-Fi and Bluetooth [2, 16]. The standard we are going to analyze in this thesis, IEEE 802.15.4-2015 standard can operate in several frequency bands, including sub-1GHz bands and 2.4GHz and higher bands [9].

Furthermore, there are other techniques that can also be employed to achieve wide area coverage, such as NarrowBand (UNB) or Spread Spectrum techniques.

Narrowband techniques are being used by SIGFOX and WEIGHTLESS-N technologies. They consist on transmitting the signals with a very small/narrow bandwidth in comparison to the available bandwidth. This modulation technique allows data transmission under highly constrained environments, as it creates a natural resistance to interference signals in addition to allowing large-scale wireless connection as it has the ability to demodulate extremely low received power signals. However, the individual data rate decreases with the increasing number of devices per unit bandwidth, which in turn limits the size and frequency of data being transmitted.

The other technique employed is Chirp Spread Spectrum (CSS), which is being employed by LoRa, RPMA developed by Ingenu and IEEE 802.15.4 [7]. Opposite to UNB techniques, CSS occupies a larger bandwidth to transmit the signal. This spreading effect mitigates the limitations on the receivers sensitivity, it increases the communication range, it is mostly immune to multi-path and Doppler effect and finally the probability of error is lower than of those of FSK [17,18]. However, all of these advantages at the expense of reduced data rate and shorter ranges than UNB.

Due to the nature of the M2M devices, they are the battery powered and very low cost, ultra low power operation is a key requirement. There are two simple employable techniques to achieve low power operation. First of all, restricting duty cycles, which lower the required power by allowing the device to enter an idle state and thus turning off the power, and turning on the power only when necessary for the transmitting/receiving state [2].

Second of all, implementing an energy efficient Medium Access Control (MAC) protocol. Opposite to the complex protocols employed for conventional cellular networks, LPWA technologies require simple MAC protocols, as the network devices are simple, low quality and low cost. For this reason, LPWA employ simple random access schemes, such as TDMA, CF/CSMA and FDMA MAC protocols [19].

The most complex and expensive protocol is TDMA/FDMA used by Weightless, Ingenu and NB-IoT. Carrier sense multiple access with collision avoidance CSMA/CA is used by DASH7 and IEEE 802.15.4, even though it is not efficient under a massive number of devices scenario [2]. For this reason, the most developed and popular technologies, LORAWAN and SIGFOX, have adopted the most simplistic and inexpensive MAC protocol, ALOHA. Moreover, utilizing the ALOHA random access MAC protocol provides diversity in channel time, which in turn partially resolves the scalability requirement in order to provide connectivity to a massive number of devices.

As previously mentioned, random access protocols have been proven to perform efficiently under a multiple user scenario. However, the main limiting factor under these protocols is the multiple access interference (MAI).

This is where Successive Interference Cancellation (SIC) techniques come into play. Under dense user scenarios with low-rate communications, these new access techniques have been developed in order to mitigate MAI.

In the receiver at the physical layer SIC schemes are being employed to increase reliability and overall performance of the systems [20]. Under multi-user AWGN channels, SIC techniques have been found to approach Shannon capacity [21]. For these reason, SIC schemes are being studied under Random Access schemes, in addition to their interaction with MAC and PHY layers. The most relevant works related to SIC research on ALOHA and 802.15.4 [22].

Furthermore, error control coding, or channel coding, is another method employed to achieve minimum error-free communication between the transmitter and receiver under a noisy channel [23].

Claude Shannon introduced in 1948 the concept of data-transmission codes, by describing the theoretical channel capacity and setting an upper bound. Channel coding is introduced in a communications system in order to encode the transmission data with the objective that in the receiver the errors, inserted by the noisy channel, can be detected and/or corrected [24].

To combat these channel errors there are in summary two types of error correcting codes [25]. First is Automatic Repeat Request (ARQ), at the receiver it tries to detect any errors in the received data. If it finds any, it alerts the transmitter of the existence of these errors so then the transmitter can resend the original data. Second is Forward Error Correction (FEC), which detects and corrects the errors at the receiver eliminating the need for re-transmission [26].

FEC is one of the most widely used channel coding methods, which is why we are going to implement this type of channel coding into our system. It is based on adding extra information to the original data so that the receiver can use this redundancy to detect and correct errors. This redundancy eliminates the need to re-transmit the data, which is why FEC are used for faster and delay dependant communications [27]. Nonetheless, this redundancy also causes the transmission bandwidth as well as the message delay and the number of errors to increase, as we are now transmitting more data than originally.

Convolutional codes have been found to be one of the best forward error correction codes among all the possible techniques for channel coding [24, 27-28]. Furthermore, they are extremely useful for continuous data transmission, therefore for real-time applications, as the encoding and decoding can be done continuously too. Moreover, one of the main differences convolutional codes has is its memory, as the output of the encoder not only depends on the present input data but on the previous results.

The best and most common approach to decode these types of codes is the Viterbi decoding algorithm, which was proposed by was proposed by Andrew Viterbi in 1967 [29], to decode convolutional codes.

This algorithm is based on maximum likelihood (ML) decoding with previous knowledge of the convolutional encoder operation, which is what aids this algorithm to be a good FEC [28]. The main advantage of this decoding method is the fixed decoding time, as it results in simple implementation. However, this complexity increases as well as the computational requirements when the memory of the convolutional code increases, which is why in real life applications this memory is usually upper bounded to around 8 [30].

IEEE 802.15.4 Standard

As previously mentioned the Standard implemented in this project is the Standard IEEE 802.15.4-2015. This standard describes the protocol for interconnecting devices in a low-rate wireless personal area network (LR-WPAN). This standard defines a simple communication network specifically designed for devices with low throughput requirements. Moreover, it defines a low complexity medium access control (MAC) sub layer plus several physical layers (PHY), which are able to operate in several frequency bands, specifically in license-free bands. The devices, for which this standard applies to, are very low-cost, with reduced data-rate and with limited battery consumption, thus low-power. Consequently, this non-proprietary standard defines a simple communication network specifically designed for devices with low throughput requirements and it is the one that best adheres to the constraints and requirements of this project.

In this chapter we are going to first of all describe the fundamentals of this standard. Second of all we will describe the system model and its implementation. Lastly, we will define several scenarios for the implemented system explained previously, in order to evaluate and analyse their performance. Moreover, an in depth analysis on the results will be conducted for each single case. In addition, a comparison between scenarios will also be executed to examine and evaluate their differences and similarities.

3.1 General Description

In this standard the architecture is defined in terms of layers, each one with a different logic and objective, similarly to other communication networks. In the following figure the device architecture is depicted, 2.

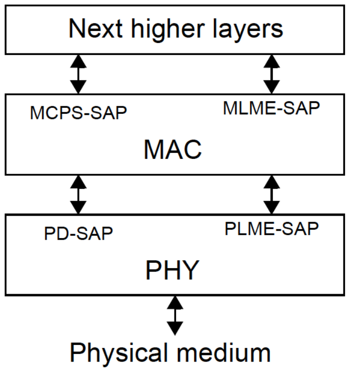

Figure 2: IEEE 802.15.4-2015 LR-WPAN device architecture [31].

Starting from the top, the “Next higher layers” includes the network and application layers, which provide the network configuration, message routing and the functionality of the device. However, these layers are out of scope of this standard and project. The next layer, the MAC layer provides the access necessary from the higher levels to the physical channel. It Lastly, the physical layer features the radio transceiver, which allows for transmitting and receiving packets across the physical channel.

3.1.1 MAC Layer

The MAC layer, as previously mentioned, controls the access to the communication or physical channel. It is responsible for the flow control and synchronization, which is done through acknowledgements and re-transmissions. Moreover, it is also in charge of providing services to the upper layers [32].

Following the requirements of devices this standard is intended to service, the MAC protocol has been optimized for low power consumption. Moreover, the standard defines the two types of devices that can be supported by the IEEE 802.15.4 network: a full function device (FFD), which is able to perform as the personal area network (PAN) coordinator therefore all the network functionalities are implemented, and a reduced function device (RFD), which is intended for extremely simple and minimal resource requirements applications and thus only supports a reduced set of network functionalities.

To cater and service both types of devices and depending on the network topology implemented, either star or peer-to-peer topology, two medium access operating modes have been characterized in addition to adopting either a slotted or unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. First, a non-beacon-enabled mode, which accesses the channel using a non-slotted or standard CSMA/CA mechanism. Second, a beacon-enabled-mode, which subdivides the time in superframes that always begin with the coordinator sending a beacon frame. In this mode the medium access utilizes the slotted CSMA/CA mechanism [31,33-34].

Moreover, this standard also adopts the contention-less ALOHA channel access mechanism. Both mechanisms are kept as possible options, which allows the device to adapt its protocol depending on the channels density and traffic. On the one hand, the ALOHA approach provides decent throughput and performance results under a light to medium traffic density channel, as it avoids unnecessary delays such as the collision avoidance phase. On the other hand, the CSMA/CA protocol has higher performance under high-density and high-traffic scenarios [31,33-35].

Even Though, the MAC layer is included and described in this standard, this project will only focus on the analysis of the physical layer. For this reason, only an introduction to the MAC layer defined in the standard is provided in this thesis. However, more information can be found directly on the standard documentation [31] or on several related articles [33-37].

3.1.2 PHY Layer

The physical layer provides an interface to connect the physical radio channel to the higher levels, specifically the MAC sublayer, by employing radio frequency hardware and firmware. The physical layer functionalities are the control of the radio transceiver, both the activation and deactivation, in order to allow data transmission and reception across the physical medium. Moreover, this layer is also responsible regarding the channel selection, energy detection (ED) and link quality indication (LQI), among others.

Due to the heterogeneity of application requirements, demand for variable and adaptable ranges and data rates, the standard defines several PHY layers in order to cater and collect under its scope all the different demands.

Therefore, the standard proposes several PHY layers, particularly 18 different physical channels, that operate employing different modulation schemes at different frequency bands. On one end of the requirements, to support the demand for high range and high data rates the standard adopts the UWB physical channel, which operates in the unlicensed UWB spectrum.

On the other end, for application with lower rates demands, longer ranges and very low power requirements, the Chirp Spread Spectrum (CSS) physical layer is defined operating in the unlicensed 2450MHz band.

In this project we are going to focus on analyzing the performance of the physical layer, specifically the Chirp Spread Spectrum (CSS) physical layer (PHY), as its the one that is specifically designed and therefore best adheres to our constraints of low rate, low power devices requirements, which depict the general characteristics of IoT devices. Moreover, this mechanism is gaining attention and it is being employed by several proprietary standards and solutions for IoT next generation devices, for the same reasons depicted above. Tha main example and proprietary technology that employs some form of these CSS techniques is LoRaWAN [38-45].

Therefore, in the next section we are going to describe in detail the physical layer chosen for this project, CSS PHY, as per the standards defines it. In addition, in this same section, we are going to introduce and define its implementation and development in order to analyze its performance under several scenarios.

3.2 Chirp Spread Spectrum (CSS) PHY Layer

As previously mentioned, we are going to focus in this thesis on the analysis of the performance of the Chirp Spread Spectrum (CSS) physical (PHY) layer that this IEEE 802.15.4 defines [31].

For this reason, we have implemented this CSS PHY layer, both the transmitter and receiver that incorporates all the specifications this standard defines. Consequently, to portray and describe our design of the CSS system implemented, in this section we are going to explain in detail the CSS PHY layer as per defined in this standard and the way it has been developed and generated.

This section is going to be organized as follows; first, we are going to explain the transmission procedure, all the different components and involved algorithms. Afterwards, we will define the reception process, again specifying all the different stages, components, algorithms and computations needed.

3.2.1 Transmission Procedure

The CSS physical layer defined in the Standard operates in the 2.45GHz frequency band and it implements Differential Quadrature Phase-shift keying (DQPSK) modulation. Moreover, it specifies a particular $r = 3/4$ symbol mapper, 8-ary bi-orthogonal mapping.

Therefore, a transmission system has been specifically developed to realize these requirements. In the following figure 3, the different pre-transmission stages and computations are depicted, which allow this transformation of the input data into the transmitted signal.

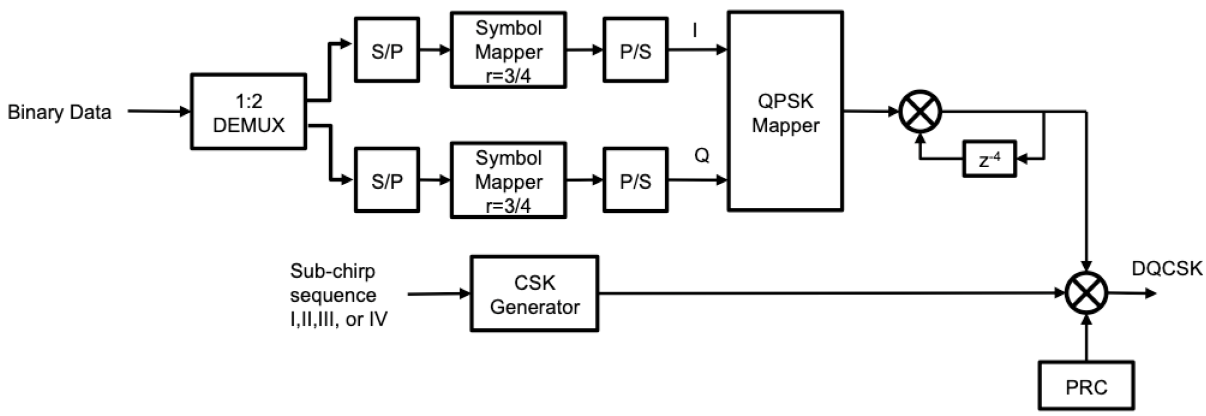

Figure 3: CSS PHY Standard Transmission Block Diagram

We are going to describe each computation needed for this transmission procedure, following the system depicted in 3, from left, the input data, to right, the output transmitted signal.

First of all, the incoming stream of binary data goes through a 1:2 DEMUX. In this stage, the input data is divided and switched each different bit into the upper or lower path, to serve the I or Q path respectively. Thus, the first bit, and all odd bits, of the input data are sent through to the I path while the second, and even, bits, are switched to the Q path. As we can observe in 3, both I and Q paths are going to follow the same procedures.

The next block, is a Serial-to-Parallel Mapping block, which separates these bits into sets of 3 bits to form data symbols. These data symbols are going to be the input into the Symbol Mapper block, which implements a 8-ary bi-orthogonal mapping $r = 3/4$, table 2. This mapper converts these data symbols, created from 3 bits of input data either from the I or Q path, into a decimal, base 10, number and then into a 4-chip bi-orthogonal codeword. This codeword, in turn, is defined as sequences of 4 chips of plus/minus ones. This Symbol Mapper, from 3 bits of data to 4 chip codeword, has been defined in the standard following the next table 2.

Data Symbol	Codeword (c0 c1 c2 c3)
0	1 1 1 1
1	1 -1 1 -1
2	1 1 -1 -1
3	1 -1 -1 1
4	-1 -1 -1 -1
5	-1 1 -1 1
6	-1 -1 1 1
7	-1 1 1 -1

Table 2: 8-ary bi-orthogonal mapping r=3/4 [46].

Subsequently, this now codeword goes through a Parallel-to-Serial block and a QPSK symbol mapping. In this stage the system maps these input codewords made from 4 chips into a complex symbol.

First of all, the Parallel-to-Serial block for each codeword joins in pairs each I and Q chip, forming 1 QPSK complex symbol. The I chip is now the real part of the complex symbol, while the Q chip is multiplied by "j" to create the imaginary part. Once we have the QPSK complex symbols, their phase is obtained, based on the specified QPSK symbol mapping phase specified in the standard, shown table 3.

Input Chips($I_{n,k}Q_{n,k}$)	Magnitude	Output phase(rad)
1, 1	1	0
-1, 1	1	$\pi/2$
1, -1	1	$-\pi/2$
-1, -1	1	π

Table 3: QPSK symbol mapping [46].

At the end of this block we have obtained all the phases of the QPSK complex symbols. With these phases, now we encounter a differential filter encoder, which converts the QPSK coding into a differential quadrature phase-shift keying (DQPSK) coding. This differential filter encoder has 4 feedback memory stages, which are all initialized to $\pi/4$ as per the standard description. This differential filter can be characterized by the following formulas in 3.1 and Figure 4.

$$x(n) = y(n) - y(n-4) \tag{3.1}$$

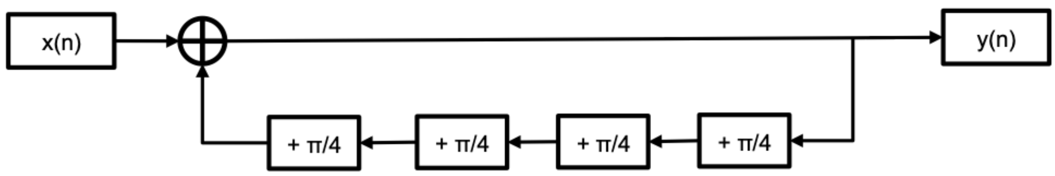

Figure 4: Transmitter DQPSK filter with 4 feedback stages all initialized to $\pi/4$.

After this filter, we now have a stream of phase DQPSK coded symbols ready to be modulated into chirp signals before being transmitted. Therefore, in this next step we are going to generate periodically a chirp sequence, with the chirp-shift keying (CSK) generator, in order to then modulate each symbol into one subchirp.

The chirp-shift keying (CSK) generator periodically generates one of the four chirp sequences specified and defined in the standard, figure 5.

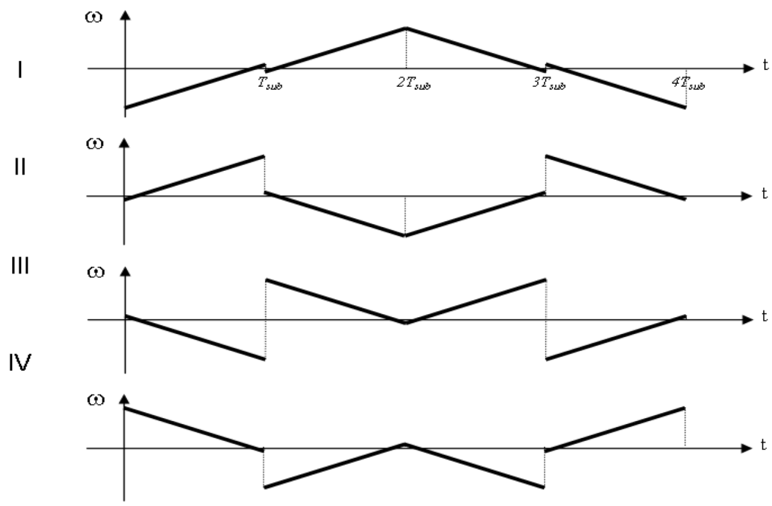

Figure 5: Four different chirp sequences [31].

This standard defines the previous four chirp sequences, I, II, III, IV. Each chirp sequence is made from concatenating four individual linear subchirp signals, which occupy two adjacent frequency subbands. The concatenation of individual subchirps, as can be seen in 6, introduces frequency discontinuities. However, these will be attenuated, and result in no affectation in the spectrum, by introducing a raised cosine windowing in the time domain.

Moreover, different time gaps are defined for each different chirp sequence and applied between consecutive chirp symbols, in order to ensure that the chirp sequences designed are almost perfectly orthogonal. These different defined gaps and timing parameters are specified in the following table 4.

Symbol	Value	Multiple of 1/32MHz
T_{chirp}	6 μs	192
T_{sub}	1.1875 μs	38
τ_1	468.75 ns	15
τ_2	312.5 ns	10
τ_3	156.25 ns	5
τ_4	0 ns	0

Table 4: Timing parameters [46].

These gaps are shown in figure 6.

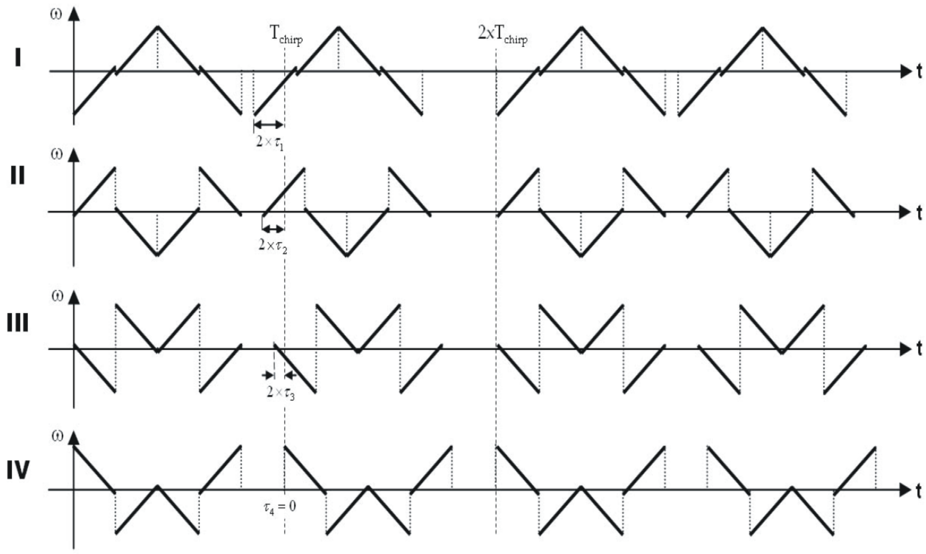

Figure 6: Consecutive chirp symbols with different time gaps [46].

Therefore, the chirp generator obtains the desired chirp signal by implementing the following mathematical equation 3.2.

$$s_m(t) = \sum_{n=0}^{\infty} \sum_{k=1}^{4} \hat{c}_{n,k} * exp\Big[j(\hat{w}_{k,m} + \frac{\mu}{2}\xi_{k,m}(t - T_{n,k,m}))(t - T_{n,k,m})\Big] * P_{RC}(t - T_{n,k,m}) \tag{3.2}$$

In this equation, m is the desired chirp signal, I, II, III, IV. The sequence number of the chirp symbols is n and the subchirp index is k. The mu is a constant $\mu = 2\pi$ x 7.3158 x 1012$[rad/s^2]$, the ξ defines the direction or slope of the subchirp and the τ_m defines the time gaps. Moreover, the center frequencies are represented by $w_{k,m}$ and the starting time of the actual chirp signal is defined as $T_{n,k,m}$, which can be represented by the following equation 3.3.

$$T_{n,k,m} = (k + \frac{1}{2})T_{sub} + nT_{chirp} - (1 - (-1)^n)\tau_m \tag{3.3}$$

After implementing the previous equations, we can obtain two pure chirp sequences with the respective gaps and chirp directions corresponding to the I (m=1) chirp sequence, as shown in the following figure 7.

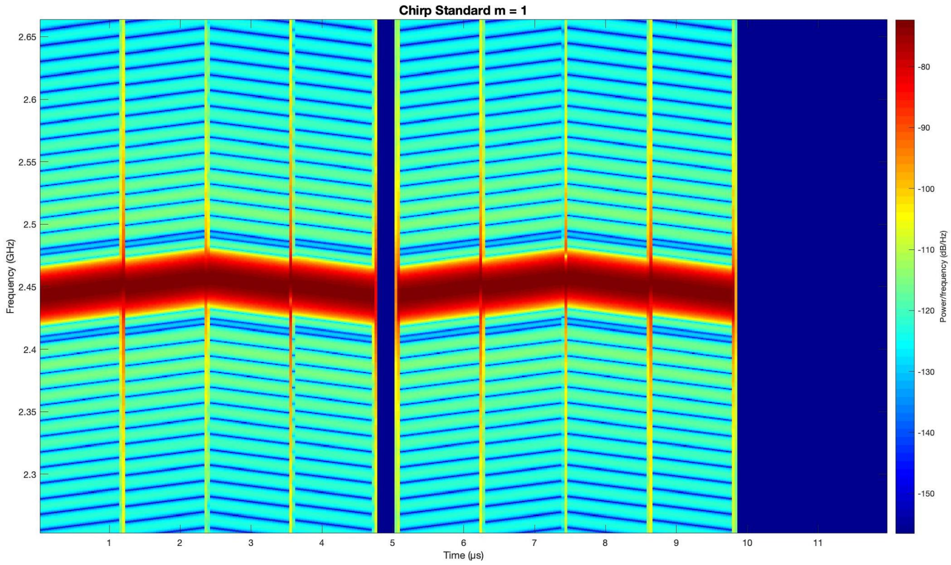

Figure 7: Chirp Sequence m=1.

As we have previously mentioned, we can observe in the previous figure the inconsistencies in the frequency jumps between each sub-chirp. To attenuate and completely resolve these frequency discontinuities found in the spectrum of a chirp sequence, caused by the concatenation of 4 different sub-chirps, a raised cosine windowing is included. The PRC defines this raised cosine window which is introduced and applied for each subchirp resulting in time domain pulse shaping. This specific windowing can be represented by the following equation 3.4 and depicted in figure 8, where $\alpha = 0'25$.

$$P_{RC}(t) = \begin{cases} 1 & |t| \leq \frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2} \\ \frac{1}{2}\left[1+\cos\left(\frac{(1+\alpha)\pi}{\alpha T_{sub}}\left(|t| - \frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2}\right)\right)\right] & \frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2} < |t| \leq \frac{T_{sub}}{2} \\ 0 & |t| > \frac{T_{sub}}{2} \end{cases} \tag{3.4}$$

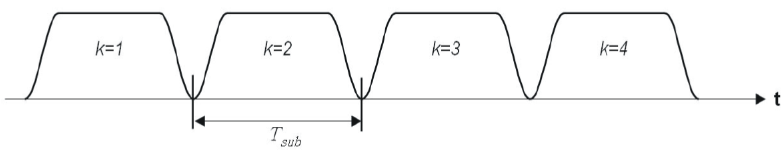

Figure 8: Raised cosine window, subchirp time domain [46].

In the following figure 9, we have implemented this PRC, raised cosine pulse defined in the standard.

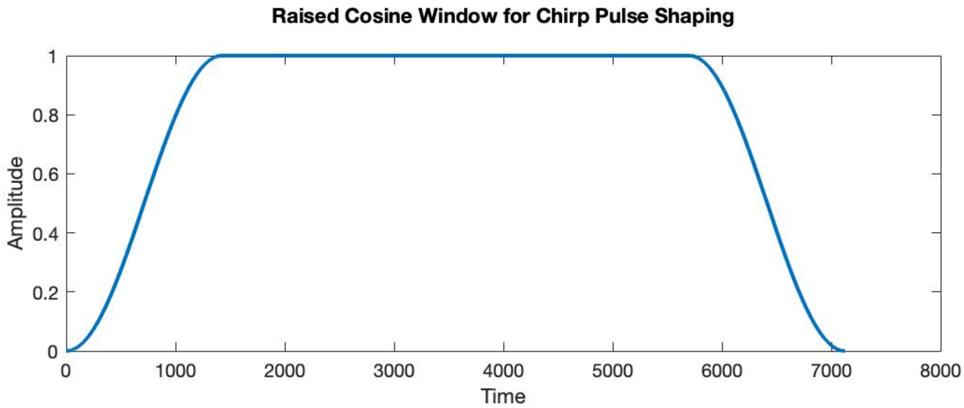

Figure 9: Raised cosine window.

The result of employing this raised cosine pulse as a windowing signal for each sub-chirp concatenated in the chirp sequence can be seen in the next figure 10. This is the result of multiplying each sub-chirp by the pulse obtaining clear sub-chirp transitions. In the figure we can observe a single chirp sequence, were it is distinctly identifiable each of the four sub-chirps with clean frequency jumps between them thanks to the windowing. This is the sequence that will transport all the data in the transmission.

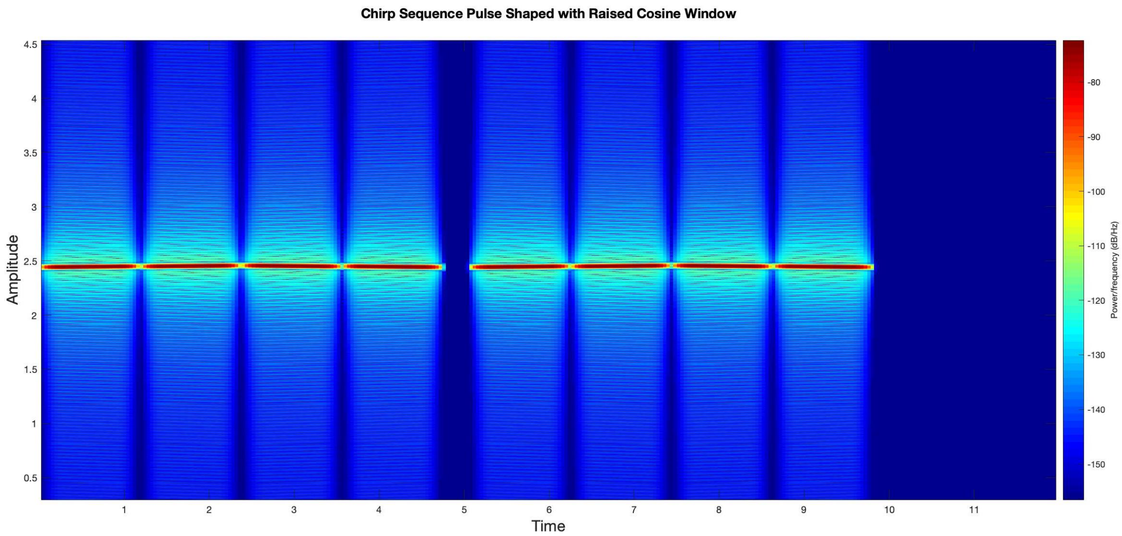

Figure 10: Chirp sequence windowed with raised cosine window.

All of these blocks and stages, converge and result in a chirp signal generated by the CSK generator, which includes the PRC sub-chirp windowing. To generate the output transmit signal, each DQPSK symbol is multiplied by the corresponding subchirp sequence.

As a result, one chirp sequence contains 4 DQPSK symbols, one in each subchirp. Therefore, the chirp symbol rate is four times lower than the subchirp rate.

The CSS PHY defined provides both subchirp sequence and frequency division due to employing alternating time gaps, different frequency sub-bands as well as different chirp directions or slopes for each of the four possible chirp signal sequences.

3.2.2 Reception Procedure

In the previous section we have explained in detail each stage and computation needed to create a CSS modulated DQPSK coded transmit signal from a simple binary data input. Now we will explain the reception procedure, which should be the complete opposite process in order to revert the signal to its initial data without any errors.

The standard only defines and explained the transmit procedure, as the reception algorithm can be extrapolated from there, as it is the same process and steps but in the opposite order. For this reason, in this section we are going to explain not the standard definition, but the receiver we have designed and implemented to achieve the complete system.

The receiver has been designed with the premise that it is an IEEE 802.15.4 standard device, and therefore it includes the four different chirp sequences and the PRC.

In the following figure 11, the reception algorithm is represented in the several blocks and steps needed to transform the input transmitted data into the output signal.

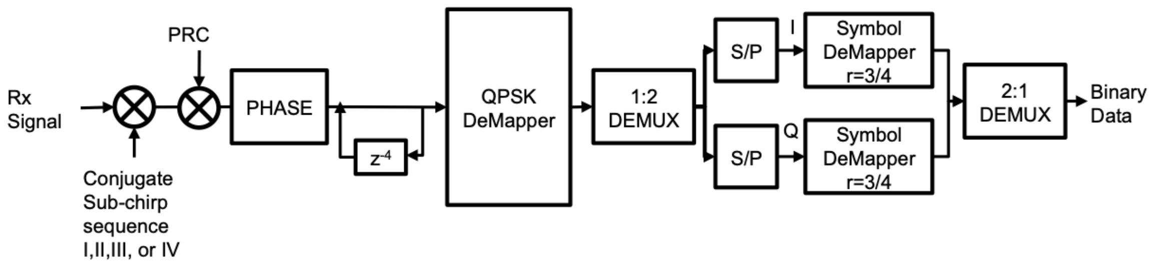

Figure 11: CSS PHY Standard Reception Block Diagram

As we can clearly observe in the figure 11, the first step is to extract the DQPSK phase symbols from the transmitted input signal. This signal has been modulated by a chirp sequence, which is why we first have to multiply the signal by the conjugate chirp sequence.

Afterwards, taking into account the different time gaps between sub-chirp sequences and the presence of the PRC pulse window shaping our signal, we can obtain the DQPSK phase by applying a simple approximation, represented in the following equation , which weights the information by the PRC pulse.

$$\hat{C}_1 = C_1 \frac{1}{N} \sum_{n=1}^{N-1} |P_{RC}(n)|^2 \tag{3.5}$$

At this stage we have obtained the DQPSK phases that depict our desired signal. Following the previous transceiver algorithm, we can extrapolate that the next step is to transform these DQPSK phases into the simple QPSK modulated phases by using an inverted differential filter.

Following the same logic, the filter depicted in the figure 12 represents a differential filter with 4 feedback or memory stages all initialized to $\pi/4$.

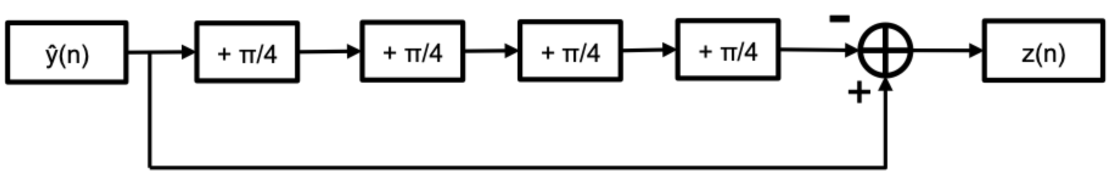

Figure 12: Receiver DQPSK filter with 4 feedback stages all initialized to $\pi/4$.

After the implementation of this block, then the following steps are straight forward. The blocks and stages are the same as in the coding transmitter process but in inverted order. Once all the blocks are correctly implemented, the output signal of the system will be the same as the input binary data stream of the system.

3.3 Scenarios & Results

In this section, as previously mentioned, we are going to define different scenarios for the implemented system explained previously, in order to evaluate and analyse the performance. Moreover, an in depth analysis on the results will be conducted for each single case. In addition, a comparison between scenarios will also be executed to examine and evaluate their differences and similarities.

There are three basic scenarios, which we will perform in this project. First, we are going to define a single user scenario, in which we are going to analyse the basic resulting performance of the implemented Standard IEEE 802.15.4 system. Then, a multi-user approach will be conducted, taking into account that in this project we are not going to implement the MAC Layer as defined in the Standard, as we want to analyse the results when multiple access interference (MAI) occurs. Consequently, it can be said that an ALOHA scheme is being implemented for the MAC Layer, thus allowing MAI to exist.

In turn, this multi-user approach will be divided into two different scenarios. First, a multi-user scenario when all the signals have the same starting time and therefore are completely overlapped. Second, a multi-user scenario when the signals have different starting times and therefore are partially overlapped.

To be able to have a reliable comparison between the obtained results, they have been simulated and obtained under the same conditions:

- Operating Frequency 2,45GHz
- Mean Unitary Aggregated Power
- Under AWGN Noise

Moreover, a soft decision system with Euclidean distance calculations has been implemented in the receiver system in order to decode the signal.

3.3.1 Single User

As we have previously mentioned, the single user scenario is the most basic of all the scenarios. It consists of evaluating the performance of the system under the instance of a single signal being transmitted and received under an otherwise completely empty AWGN channel.

In the Chirp Spread Spectrum (CSS) Physical Layer defined in the Standard there are four different chirp-modulating signals designed. In order to obtain reliable performance results and to observe any differences in the outcome, we are going to conduct this scenario for each of the different chirp modulations signals. For this reason, we are going to obtain four system performance results.

To obtain the performance results of this scenario, no changes are needed to the implementation of the standard. Consequently, the complete system scheme will be the following:

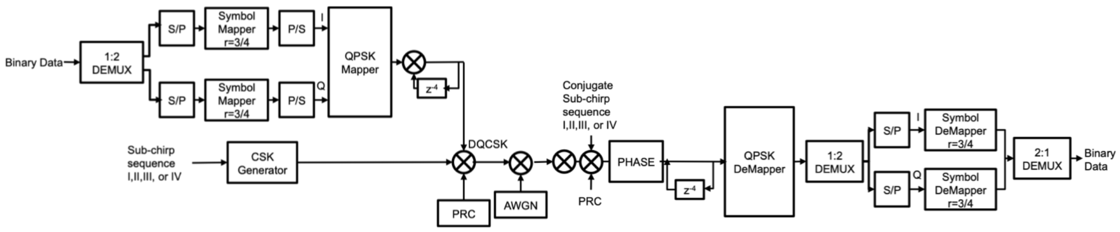

Figure 13: Standard Complete Transmission and Reception Block Diagram

The results obtained for the previous implementation under this scenario can be observed in the following figure 14. In this figure we can observe the obtained performance curve for the standard for a single transmitted user under an AWGN channel. Moreover, we have included as reference the theoretical performance result for a bi-orthogonal signal with coding k=3, same as our system.

The differences between our system results and the theoretical curve are due to efficiency losses implicitly included in the definition of the Standard transmission and reception system.

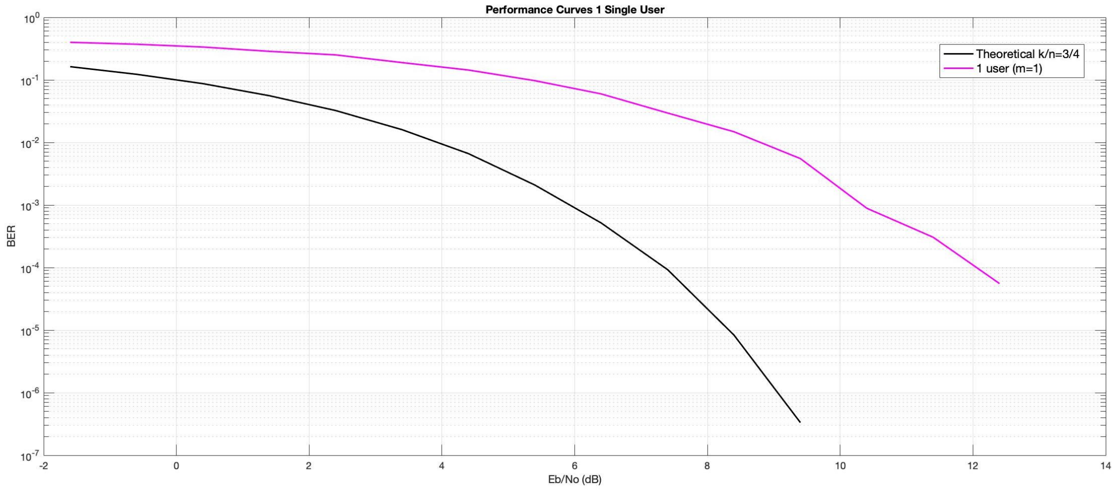

Figure 14: Single Chirp (m=1) vs. Theoretical bi-orthogonally coded transmission with k=3 [47]

The definition of the IEEE 802.15.4 CSS standard is introducing several aspects, which causes a reduction and deterioration in performance results. The standard defines a system in which Chirp sequences are used in turn with different time gaps, during which no signal is being sent thus causing efficiency losses and as a result the performance deteriorates in comparison to a full continuous signal. Moreover, the signal is windowed by a cosine pulse (PRC) to lower the effect of the frequency jumps. However, this windowing further includes efficiency losses in the signal.

We can perform a rough estimation of the efficiency losses due to the previous effects. For this, we must consider the time the signal is not transmitting due to the gaps and the windowing from the pulse. Therefore we have the following equations:

$$T_{GAP} = T_{chirp} - 4 * T_{sub} = 6\mu s - 1.1875\mu s = 6\mu s - 4.75\mu s = 1.25\ \mu s \tag{3.6}$$

$$Losses\,Gap = 4 * T_{sub}/T_{chirp} = 4.75/6 = 0.7917\ (lin) \tag{3.7}$$

$$Losses\,PRC = P_{tx}^{T} * P_{tx}/lengthtxsignal = 0.75\ (lin) \tag{3.8}$$

$$\begin{aligned} Total\,Losses &= 10 * log_{10}(Losses\,Gap * Losses\,PRC) \\ &= 10 * log_{10}(0.7917 * 0.75) = 10 * log_{10}(0.5938) = -2.2636\ dB \end{aligned} \tag{3.9}$$

Furthermore, the standard includes a differential filter with a memory of 4. This filter is causing the overall performance of the system to deteriorate in comparison to a system without it. This is because, if there is an error in the decoding of the received signal, this error is being propagated through the filter, turning one single error into two.

However, the memory of the filter, four, is allowing these two errors, the original and the propagated, to not be consecutive and therefore affect two different codewords instead of a single one. If the two errors where in the same codeword, the receiver would have zero probability to decode correctly that codeword. However, as they are in two different codewords, the receiver has a higher probability of correctly decoding the codewords. Nonetheless, this filter is causing an overall deterioration of the system as it is duplicating errors. The worst-case scenario being that all the errors are duplicated and are not correctly decoded.

We have performed this analysis for all of the four different chirp sequences, figure 15. As expected, we can clearly perceive that the performance results are the same for all the different chirp modulation signal, as none other modification has been made to all the other parameters involved in the system.

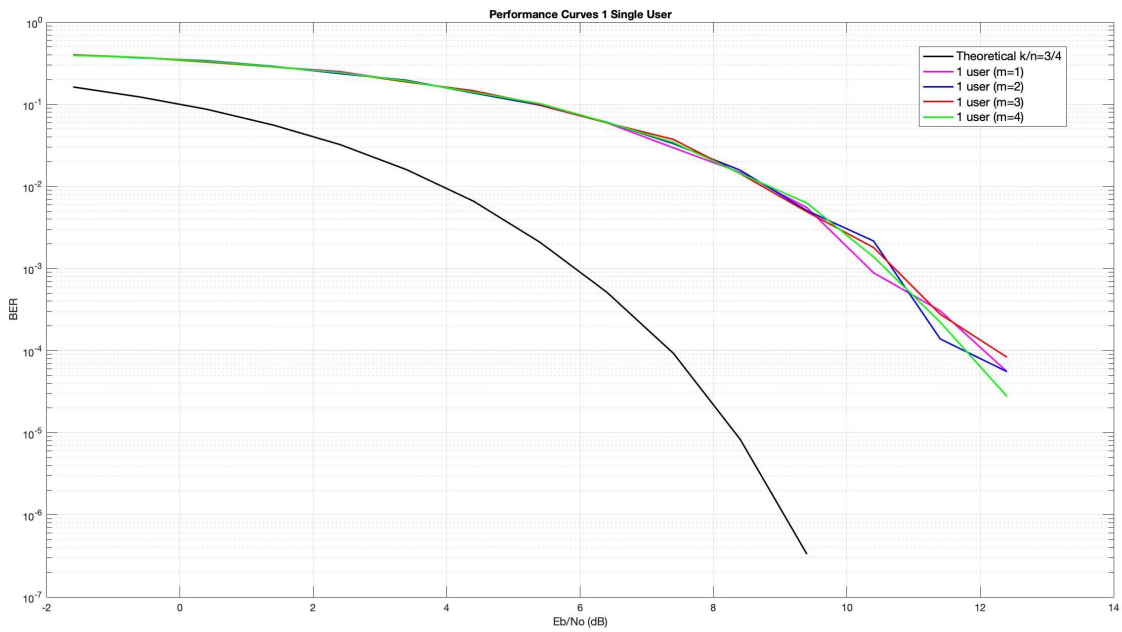

Figure 15: Standard Performance Results under Single User Scenario

3.3.2 Multi-User equal times

This scenario consists of a multi-user system when all the signals have the same starting time and therefore are completely overlapped. The Standard has defined four different chirp modulation signals with different gaps, which have been chosen to make the four chirps almost completely orthogonal [31]. Therefore, we are going to test this orthogonality between chirps by creating this scenario in which two or more signals are transmitted at the same time but each one with a different chirp modulation signal. Consequently, if the chirp signals are sufficiently orthogonal between them then we should expect to obtain similarly results as in the single user scenario.

This scenario can be subdivided in three cases depending on the number of users that are being transmitted at the same time. For this reason, first we are going to obtain the results and analyse separately each case, 2, 3 and 4 user signals. Lastly, we will analyse and compare all of the previous results obtained.

3.3.2.1 Two Multi-user signals Results

First of all, we are going to obtain performance results under a two-user scenario. Both users signals will be modulated separately with two different chirp modulation signals and then transmitted at the same time. This means that both transmitted signals will be completely overlapped and interfere with each other at the receiver. This scenario does require the system implemented for the standard to be modified, but minimally. From the single user system implementation, we can define the following blocks as shown in the figure 16.

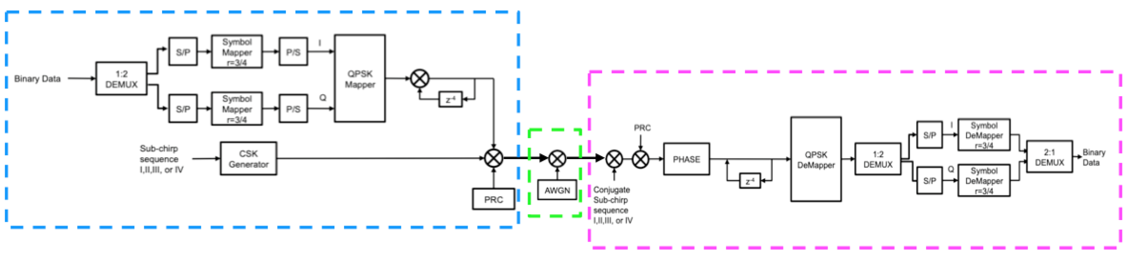

Figure 16: Single User Standard System Implementation Block Diagram

From the previous designed blocks, we can design the multiple-user scenario with the following block scheme, figure 17.

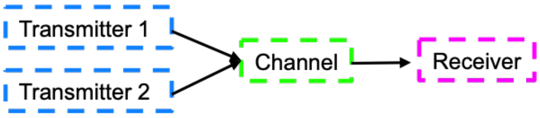

Figure 17: 2 Multi-User Standard System System Block Diagram

Furthermore, we can previously analyse the expected results by comparing the orthogonality of the chirp signals beforehand. We are going to extract the performance results of all the pair combinations of chirps, which results in six possible pairs, as we are excluding permutations, as shown in the table 5 below.

User Signal 1	**User Signal 2**
Chirp m = 1	Chirp m = 2
Chirp m = 1	Chirp m = 3
Chirp m = 1	Chirp m = 4
Chirp m = 2	Chirp m = 3
Chirp m = 2	Chirp m = 4
Chirp m = 3	Chirp m = 4

Table 5: Possible combinations of two different chirp sequences

For each combination, we can analyse the orthogonality of the Chirp Signals taking into account that they are being transmitted at the same time. Therefore, we can overlap the signals to detect points in time, which due to the overlap, they are going to be interfering with each other. In the following figures, we can observe the result of overlapping the chirp signals, figure 18.

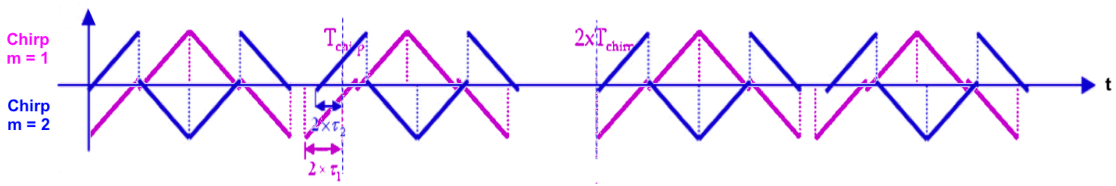

Figure 18: Chirp m=1 and m=2 Sequences Overlapped

As we can observe in the previous figure, 18, these two sequences are mostly completely orthogonal as they only interfere for the center frequency in the instances there is a frequency jump. Thus resulting in minimal mutual-interference between them.

If we analyze another combination, such as in the following figure 19, these two sequences, 1&3, are less orthogonal than the previous combination. They interfere in several points when the two signals are overlapping. For this reason, we expect the performance results to be affected and therefore deteriorated in comparison to the previous combination of Chirp 1 and 2.

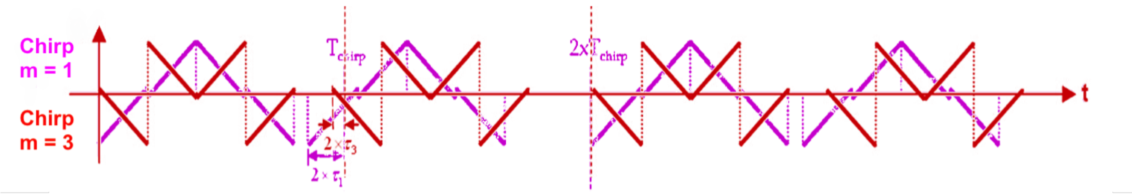

Figure 19: Chirp m=1 and m=3 Sequences Overlapped

The rest of the possible combinations are shown in the following figures.

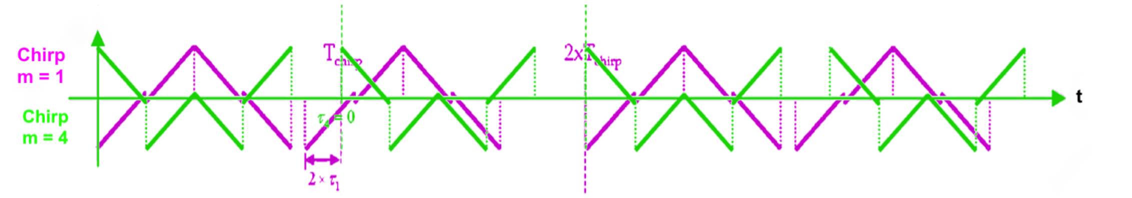

Figure 20: Chirp m=1 and m=4 Sequences Overlapped

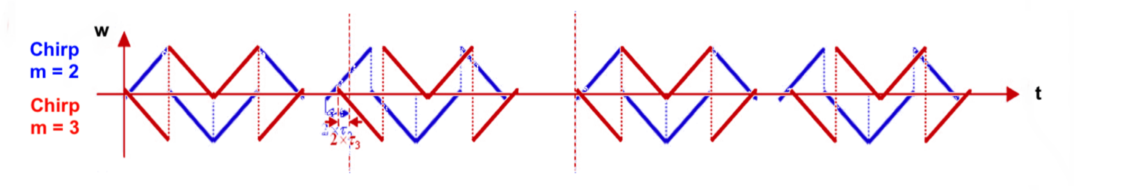

Figure 21: Chirp m=2 and m=3 Sequences Overlapped

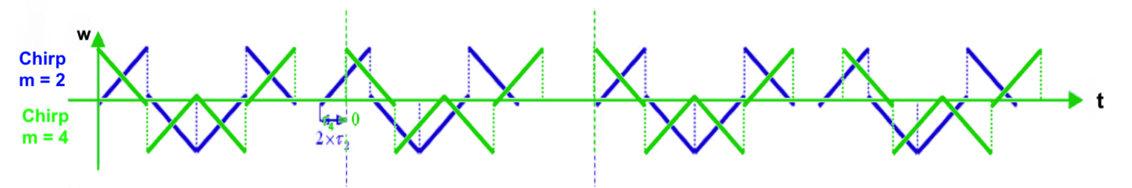

Figure 22: Chirp m=2 and m=4 Sequences Overlapped

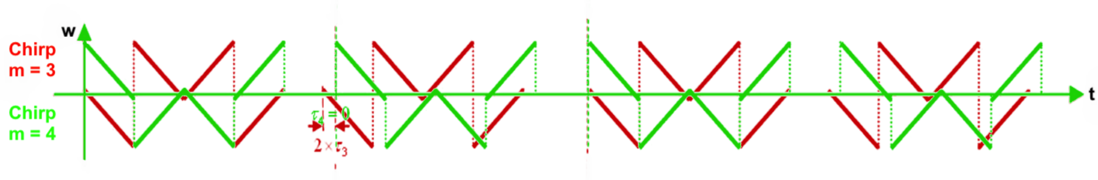

Figure 23: Chirp m=3 and m=4 Sequences Overlapped

From the previous figures, we can observe the points where the combinations cross and interfere with each other. For this reason, we can expect the performance results to be better for the 1&2, 1&4, 2&3 and 3&4 combinations than for the 1&3 and 2&4.

In the following figure we can observe the results of performance of the system under the defined multi-user scenario, specifically 2 users transmitting different signals at the same time 24.

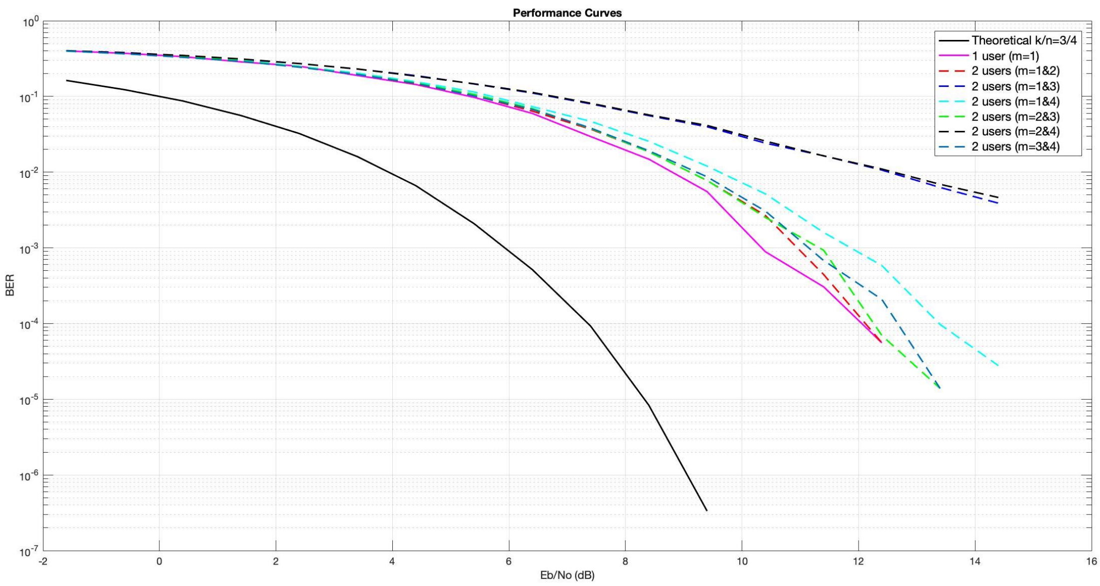

Figure 24: 2 Multi-User Scenario Standard Performance Results with Synchronism

As we can clearly observe in the previous figure the two combinations that have worst performance results are for the 1&3 and 2&4 as expected. These chirp sequences have been designed with the same side-band with the frequency ramps going the opposite way. The other combinations have similar performance results between them as the interference between the signals are relatively equal. We should note that the worst combination, between the relatively good performing ones, is the 1&4, as both sequences overlap in the middle of a sub-sequence in addition to the overlaps in the frequency jumps, the interference points can be observed in 20.

3.3.2.2 Three Multi-user signals

Similar to the previous section, there are only four possible combinations between the 4 chirp sequences, excluding permutations, as shown in the table below.

User Signal 1	**User Signal 2**	**User Signal 3**
Chirp m = 1	Chirp m = 2	Chirp m = 3
Chirp m = 1	Chirp m = 2	Chirp m = 4
Chirp m = 1	Chirp m = 3	Chirp m = 4
Chirp m = 2	Chirp m = 3	Chirp m = 4

Table 6: Possible Combinations of 3 Chirp Sequences

In the following figure we can observe the results of performance of the system under the defined multi-user scenario, specifically 3 users transmitting different signals at the same time 25. We can observe that the four combinations yield similar results, as they suffer from similar number of overlaps and interferences.

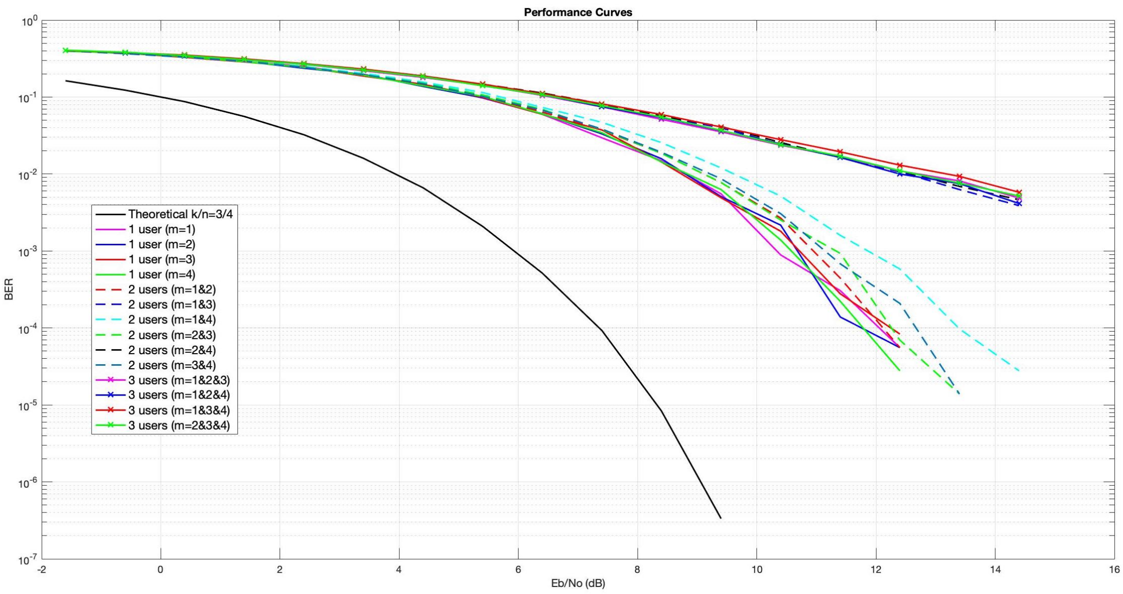

Figure 25: 3 Multi-User Scenario Standard Performance Results with Synchronism

Moreover, we can observe that the four triple combinations result in the same performance results than for the pairs combinations 1&3 and 2&4.

The interferences caused between these signals dominates the overall performance of the system. They yield the same results as in each of the triple combinations there is one of the pairs with worst interference.

3.3.2.3 Four Multi-user signals

In the following figure we can observe the results of performance of the system under the defined multi-user scenario, specifically 4 users transmitting different signals at the same time 26.

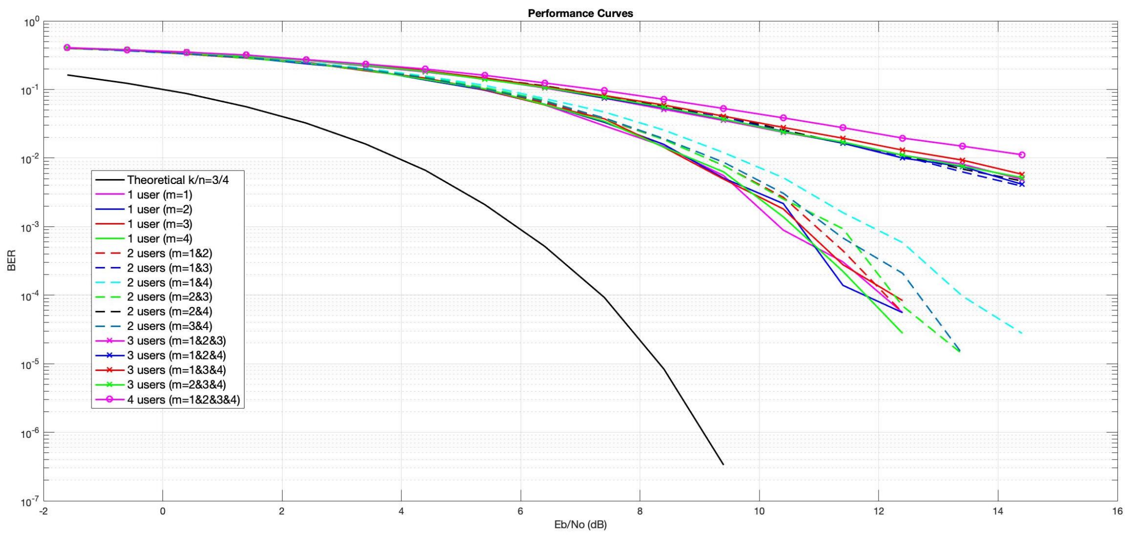

Figure 26: 4 Multi-User Scenario Standard Performance Results with Synchronism

In this figure we can observe the expected deterioration of the overall performance results as we have four simultaneous interfering signals.

We can conclude that the main factor for the reduction in the overall performance results are the overlaps that are not in the centre frequency or due to the frequency jumps, but because the signals cross and interfere with each other.

Moreover, we can conclude that the interferences introduced by the non-orthogonality of the pairs combination 1&3 and 2&4 dominate the degradation overall performance, which is why the results have minimal variation and deterioration when introducing 1 or 2 extra users into the system where one of these combinations pre-exists.

3.3.3 Multi-User different times

In the previous section we have analysed the performance of the system under a simple multi-user scenario. However, in that scenario some synchronism is needed as we are assuming that all the transmissions are done for the same starting time. In this section, we will introduce a more realistic scenario where time synchronism is not included, thus the signals will be received with different starting times.

We have to take into account that the standard defines the chirp sequences and time gaps in a way that the signals are mostly orthogonal between them. However, it is assumed that this orthogonality is only achieved when they are transmitted and received synchronously, which won't be applied in this new section. Consequently, we expect the performance to be inferior than for the synchronized scenario.

To define this non-synchronism, we have implemented in our system delays between transmissions. These delays should have been implemented as arbitrary times in order to simulate a real scenario. However, we manually determined different starting times in order to simulate different possible scenarios and we obtained the same results for all cases. These delays have been selected manually in order to test the chirp sequences orthogonality, which in the standard is accomplished by the use of the different gaps between a period of chirp signals. In order to obtain relevant results, we have selected different delays so each one defines a different scenario.

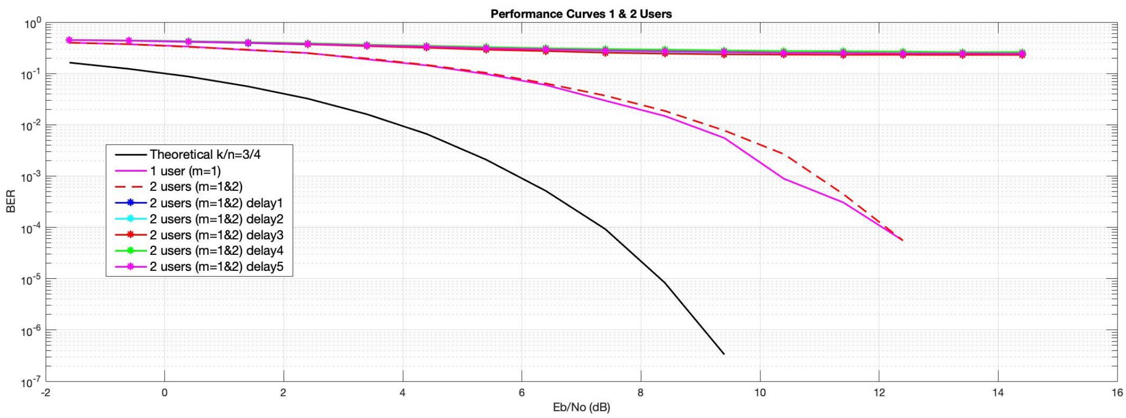

Figure 27: 2 Multi-User Scenario Without Synchronism Standard Performance Results (Chirp m = 1 & 2)

In the previous figure we have represented the overall performance of the system under the combination of chirp 1 and 2 with different starting times, figure 27.As we can observe, the different delays yield the same results, as the curves are all overlapped. From this result, we can conclude that this standard requires some type of synchronization control under a multi-user scenario in order to yield acceptable performance results.

We have tested this scenario for the other pairs of combinations and we have found the same results, figure 28. They all result in a similar performance curve, they are all overlapped.

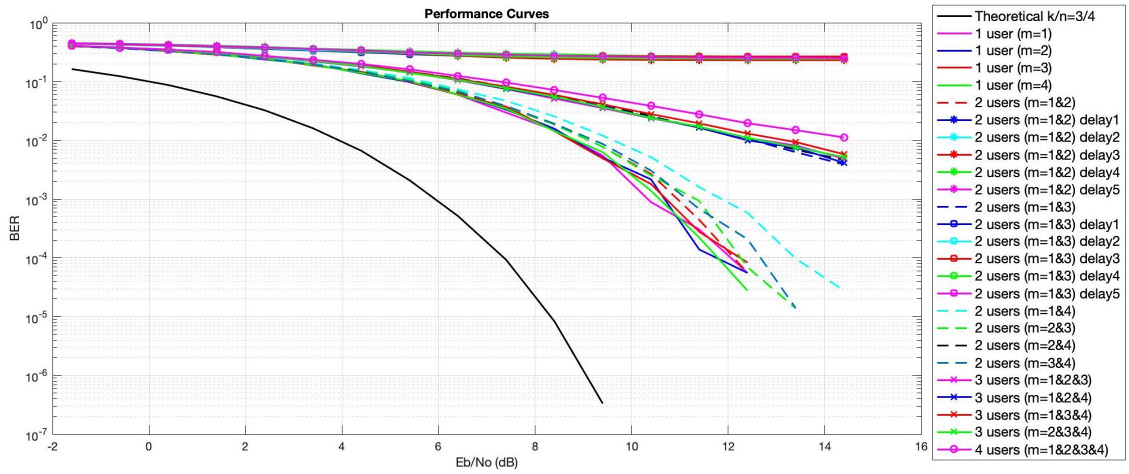

Figure 28: Comparison between Standard Performance Results with and without Synchronism

Consequently, this standard must indeed include some synchronization mechanism for multi-user scenarios under a random access protocol. Due to the definition of the chirp signals and their gaps, their orthogonality is only reached and maintained when there are no delays between them. If the chirp sequences are not able to obtain this level of orthogonality it causes the overall system to fail and result in appalling performance curves.

Due to the previous results, we have not performed this analysis for combinations of three users or four as the results are only expected to be the same or worse, following the logic and results in the previous synchronous multiple-user scenario.

SIC Techniques

4.1 Introduction

As mentioned in the introduction, this study focuses on analyzing the performance results of implementing the IEEE 802.15.4 standard under a multiple user scenario. It is in this type of environment where Random Access Protocols have been found to be a key element of communication systems.

However, under these protocols the main limiting performance parameter is the multiple access interference (MAI) or inter-user interference. It is in this respect where interference cancellation (IC) policies have proved an invaluable tool in order to counteract this problem.

For this reason, in this project we will implement these techniques, specifically Successive Interference Cancellation (SIC) techniques to evaluate the performance of the system before and after to observe the variation. Thereafter, in the following section SIC techniques are going to be introduced and defined. Moreover, the theoretical equations, scheme and following implementation into our system is going to be detailed. Afterwards, we will outline and characterize all the different scenarios and compare the results with and without the application of these methods in order to evaluate their features and performance. Additionally, we will analyze the effectiveness of these techniques under the different scenarios.

4.2 System Model

Interference Cancellation techniques are divided into two main categories, pre-IC and post-IC, which differentiate mainly on where on the systems they are applied.

On one hand, pre-IC techniques are applied in the transmitter side, thus based on the suppression of interferences on a priory basis. Some of these schemes take into account the interference experienced and obtained at the receiver to then apply counteractive measures in the transmitter order to suppress it.

Therefore, in order to effectively estimate the interference suffered in the receiver reliable Channel State Information (CSI) is required. The more accurate the CSI is the effective pre-IC techniques are. As a result, this required reliable CSI, in real conditions is very complex to accomplish, which results in an imperfect CSI and thus yielding a lower overall system performance than theoretically estimated [48].

On the other hand, post-IC techniques are implemented in the receiver side with the objective of suppressing interferences on a posteriory basis. These schemes require signal processing at the receiver thus the introduction of CSI is not required. Consequently, these techniques are less complex in addition to being more flexible and adaptable than pre-IC.

Post-IC techniques can be divided into two subcategories; either Parallel or Successive. Parallel Interference Cancellation (PIC) is based on the simultaneous detection of all the users, which then allows for the cancellation of some of the interference. This approach is highly susceptible to errors in addition requiring complex hardware to implement it.

The more attractive methodology is Successive Interference Cancellation (SIC), which proposes a sequential decoding of the users, when all are received simultaneously[49].

Successive interference cancellation (SIC) the key performance factor for decoding success is the heterogeneous distribution of the received power of each of the users. This is because the iterative algorithm proposed in SIC decodes the users sequentially in the order from highest to lowest received power.

The receiver implemented with SIC techniques will perform the following scheme and algorithm, figure 29.

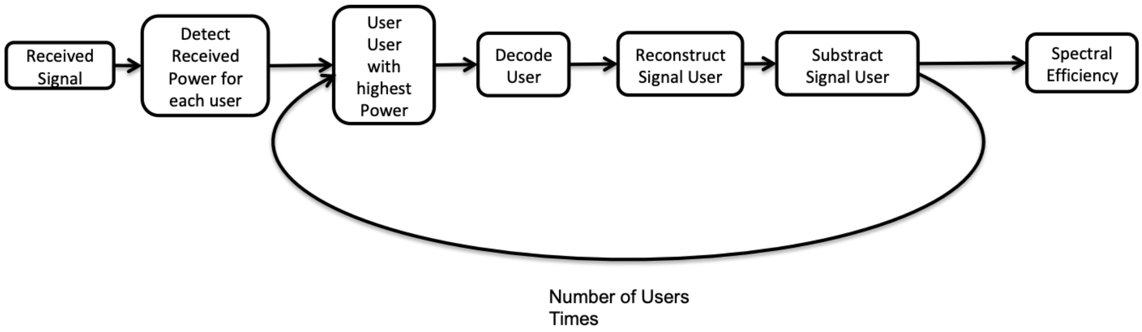

Figure 29: Successive Interference Cancellation (SIC) scheme

Following the scheme shown in the previous figure, the algorithm performs the following steps. The receiver, which applies SIC, first will decode the user received with the highest power. This decoding will be done by treating the other users as interferences. Once this first user has been decoded, the receiver will reconstruct the waveform for this user in order to then subtracted from the composed received signal. Afterwards, the receiver once again will decode the next user with the highest power from this subtracted composed received signal. These steps will be repeated sequentially, following the order of highest to lowest power of the received users until all the users have been decoded.

When implementing SIC, one of the users, $user_1$ is decoded at the receiver treating all the other users, so $user_2$, as interference. However, when $user_2$ is decoded, we are using the aggregated received signal with the benefit that the signal of $user_1$ has been removed. As a result, the SIC scheme has enhanced overall performance at the receiver than a conventional scheme, which decodes every user treating the others as interference.

Theoretically, at the end of this scheme all the users have been decoded perfectly. However, in practice, the decoding of the users can be defective, therefore affecting not only that single user but the decoding of the following users. If a user is not decoded perfectly, then in the subtraction step some residual signal will remain thus affecting the next users decoding. Nonetheless, these schemes have been extensively studied and proven to enhance the resulting performance of systems under multiple access interference (MAI) [48-54].

Additionally, these schemes are less complex than other methods being studied as they are based on the decoding of one packet at a time, and therefore are quite simplistic. For this reason, in this thesis we have implemented these SIC techniques in the receiver, in order to evaluate the enhancement in performance under various multiple users scenarios.

4.3 Scenarios & Results

In this section we will implement the previously explained Successive Interference Cancellation (SIC) techniques in the receiver in order to evaluate the enhancement of these under this particular standard. Following the previous results, we will test and analyse these schemes under a multiple-user synchronous scenario, in where the chirp sequences do achieve orthogonality.

As previously mentioned, the key performance factor for decoding success while employing SIC techniques is the heterogeneous distribution of the received power of each of the users. To this end, we have defined several scenarios where the difference is the distribution of the power between the users. However, to have a reliable comparison between the results, not employing SIC techniques and including them in the scheme, we will define both scenarios under the same unitary overall average signal power.

This analysis has been performed in a general capacity, therefore the optimal power distribution hasn't been found, as we have manually set the distribution of power in order to get a general idea of the results. Therefore, a future improvement would be to optimize the power distribution in order to get the best results.

4.3.1 2 Multi-User equal times with SIC Techniques

In this subsection we have created a multiple user scenario, specifically 2 users, while at the receiver implementing SIC techniques. We have defined various power distributions for both users, in order to accomplish the necessary heterogeneous distribution needed by the SIC techniques to result in a positive performance.

Due to the different results obtained under a simple 2-user scenario, we are going to perform this analysis for two different combination of chirp sequences, Chirp 1&2 and Chirp 1&3, in order to analyze the performance results under different level interfering sequences. From the previous analysis, we obtained better performance results for the combination 1&2 than 1&3, due to the interferences the chirp sequences caused between them.

First of all, we are going to analyze the results of including SIC techniques in the receiver under a two user scenario with different signal power, Chirp 1&2, in 30.

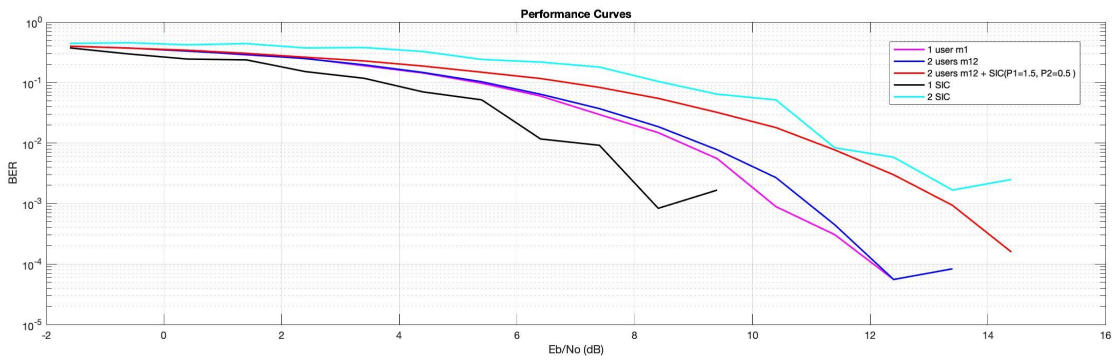

Figure 30: 2 Multi-User with SIC Techniques Chirps m=1&2 showing individual and Overall Performance Results

In figure 30 we can observe the performance results for this scenario, showing the performance curves for the overall system, red curve, in addition to the single user results, pink curve. The user with highest signal power, $P_1 = 1.5$, following the SIC algorithm, is the first signal to be decoded, black curve. This decoding is done assuming the user 2 signal as interference in addition to the noise. As we can observe, the results have improved in respect to the 2 user scenario without power distribution, dark blue curve, by a factor of around $10log_{10}(P_1) = 10log_{10}(1.5) = +1.76dB$.

Once the signal with higher power has been decoded, the algorithm recreates the signal and subtracts it from the original received signal, and decodes the user 2 signal, light blue curve. This second signal has lower power, however as we have removed signal 1 the only interference term is the noise. For this reason, these results have to be compared with the performance curve obtained for a single user scenario, pink curve. Following the previous logic, as the signal has lower power, the resulting performance should be impacted by a factor of around $10log_{10}(P_2) = 10log_{10}(0.5) = -3dB$ in respect to the single user performance curve, which has unitary signal power. We can observe in the previous figure that the performance results for the second user have been affected by this lower signal power, affecting negatively in the results.

Averaging both results, we obtain the overall performance curve of this multi-user SIC scenario, red curve. As we can observe, under these conditions and scenario the SIC techniques applied in the receiver are not benefiting the performance results. Nonetheless, the key performance factor under these schemes is the power distribution. For this reason, in 31 we can observe the different resulting averaged performance curves for a 2-user scenario with SIC schemes in the receiver under different heterogeneous power distributions for the combination of chirp 1&2 sequences.

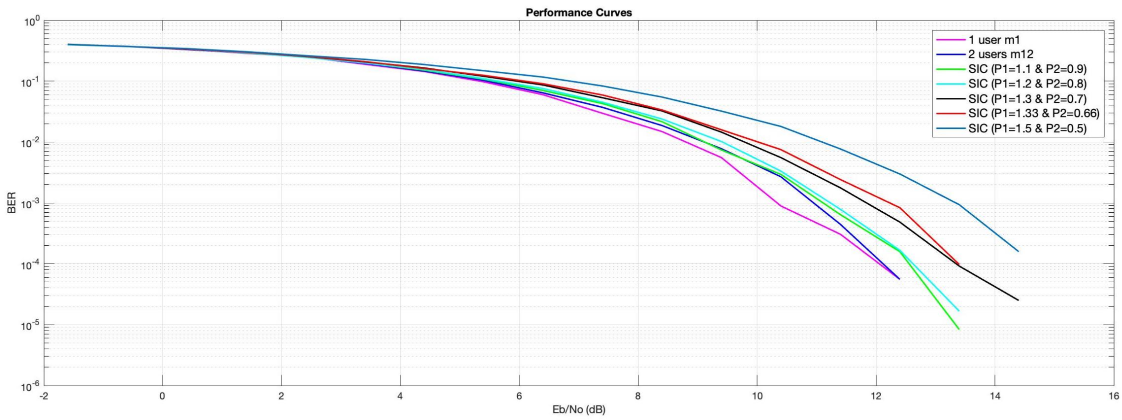

Figure 31: 2 Multi-User with SIC Techniques for different Power Distributions Overall Performance Results (1&2)

As we can appreciate from the figure, the application of SIC schemes in the receiver in a 2-user scenario, chirp 1&2 sequences, defined with the IEEE 108.15.4 protocol is not benefiting the results. The heterogeneous distribution of power in negatively affecting the average results of the scheme, as the user with lower power is dominating these results. However, similar performance is obtained when the distribution of power between the signals is almost unitary. Nevertheless, better results are obtained for a simple receiver without the application of the SIC techniques, but with homogeneous power for all the users.

Additionally, we have performed the same simulations under the same scenario, now for chirp 1&3 sequences, to evaluate the results under a more interference ridden scenario, figure 32.

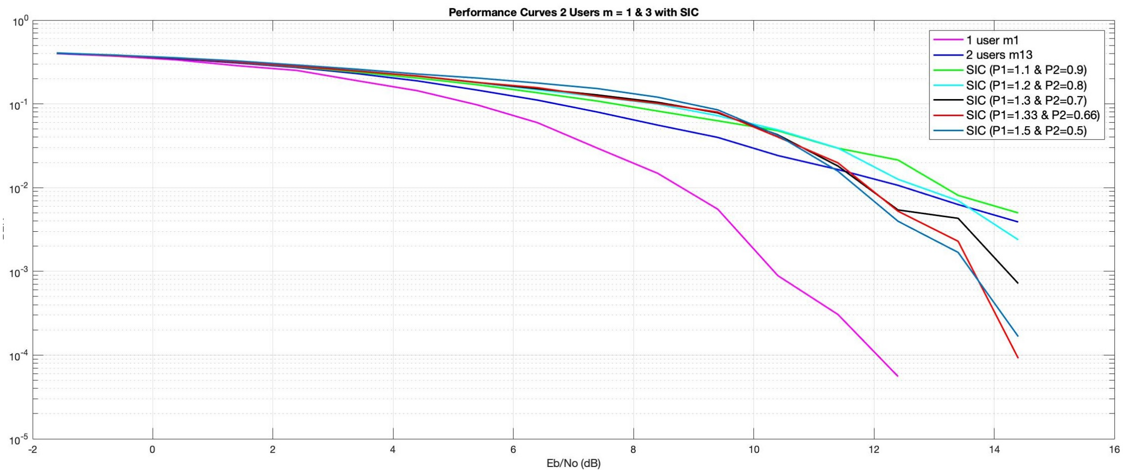

Figure 32: 2 Multi-User with SIC Techniques for different Power Distributions Overall Performance Results (1&3)

From the previous figure we can conclude that at low signal to noise ratios, low Eb/No, under this specific scenario the simple receiver, defined previously for the standard, is outperforming all the other results. However, under improved conditions, high Eb/No, and under this specific scenario SIC techniques enhance the performance results. Moreover, these techniques are additionally enhancing the performance results under highly heterogeneous distribution of power.

From these two analysis we can conclude that the SIC Techniques enhance the overall performance results for the system when under high interference conditions. As previously mentioned, the combinations of the chirp sequences 1&3 highly interfere between them, as they share frequency sub-bands with opposite slopes causing overlaps between them, which in turn causes their overall performance to deteriorate. The opposite case is between the chirp sequences combinations 1&2, which hardly overlap due to being highly orthogonal, thus obtaining better performance results.

For both scenarios we have applied these SIC techniques and after reviewing the results we can determine that for low interference scenarios these techniques damage the performance instead of enhancing it.

However, these techniques are highly valuable and efficient under high interference scenarios. They obtain similar results than the original standard under unfavorable signal to noise conditions. Whereas under great conditions the enhancement in performance these techniques contribute to the system are considerable and clearly observable in figure 32. Moreover, the best results for this scenario applying SIC techniques are obtained when under highly heterogeneous scenarios, as we can observe for the performance curves under a distribution $P_1 = 1.5$ and $P_2 = 0.5$ in a green-blue hue, or $P_1 = 1.33$ and $P_2 = 0.66$ in red.

4.3.2 3 Multi-user signals with SIC Techniques

In this subsection we have created a multiple user scenario, specifically 3 users, while at the receiver implementing SIC techniques. We have defined various power distributions for the three users, in order to accomplish the necessary heterogeneous distribution needed by the SIC techniques to result in a positive performance. Similarly to the previous analysis, are going to compare the results with the simple 3-user scenario without SIC schemes in order to easily appreciate the performance results.

First of all, we introduce in 33 the performance results for the overall system in addition to the single user results.

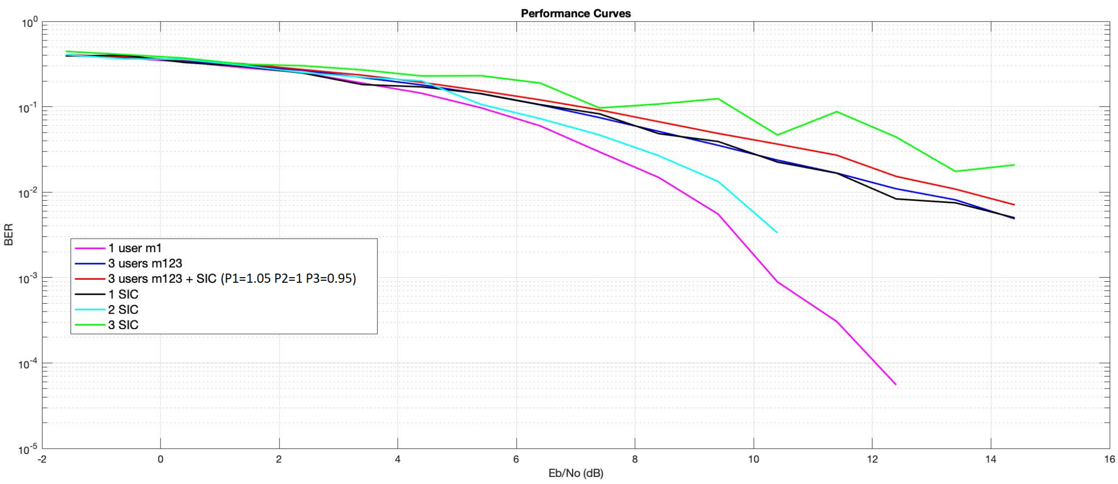

Figure 33: 3 Multi-User with SIC Techniques Chirps m=1&2&3 showing individual and Overall Performance Results

The user with highest signal power, black curve, is the first to decode, thus has the other two signals as interference with the noise, which is why it obtains similar performance results as the standard under the three multi-user scenario, dark blue curve. As the difference between the power of the signals is not relevant, it differs around 0.5, the gain from that increase in power is minimal which is why we obtain similar results without any performance enhancement. The second user to be decoded, light blue curve, we can clearly observe how it has been enhanced from the results from the standard under the three multi-user scenario, dark blue curve. This is because this user under SIC techniques, only has as an interference the third user and the noise, as it has decoded and extracted the first user.

Last of all, the third user is deteriorating our overall performance results. The third user would be expected to result in the best performance, as we have now only the noise as an interference, as the SIC techniques has already extracted user 1 and 2. However, this enhancement can not be observed due to the decoding errors of the two previous users, which makes the extraction of the signals to contain multiple errors, increasing the noise and interference factor.

As we can observe the second user obtains the best results, almost the same performance as a single user scenario. However, the other two users performance are greatly affected by the reduction of the signal power obtaining deplorable results. As a result, the overall performance of the system with the receiver implementing SIC schemes, in addition to heterogeneous distribution of power, is worse than without these schemes but with homogeneous power distribution between users.

However, as we have previously mentioned the main factor on the resulting performance of the SIC techniques is the power distribution between the users. Therefore, to properly analyse the performance of the 3 multi-user scenario, we have to simulate and extract results for this same scenario under several different power distributions, as seen in the following figure 34.

From the following results we can observe similar results than for the previous 2 multi-user scenario employing SIC techniques. From the figure 34 we can conclude that at low signal to noise ratios, low Eb/No, both systems, with and without SIC, obtain similar results. For intermediate conditions, and under this specific scenario, the standard is outperforming all the other results. However, under improved conditions, high Eb/No, SIC techniques enhance the performance results of the standard.

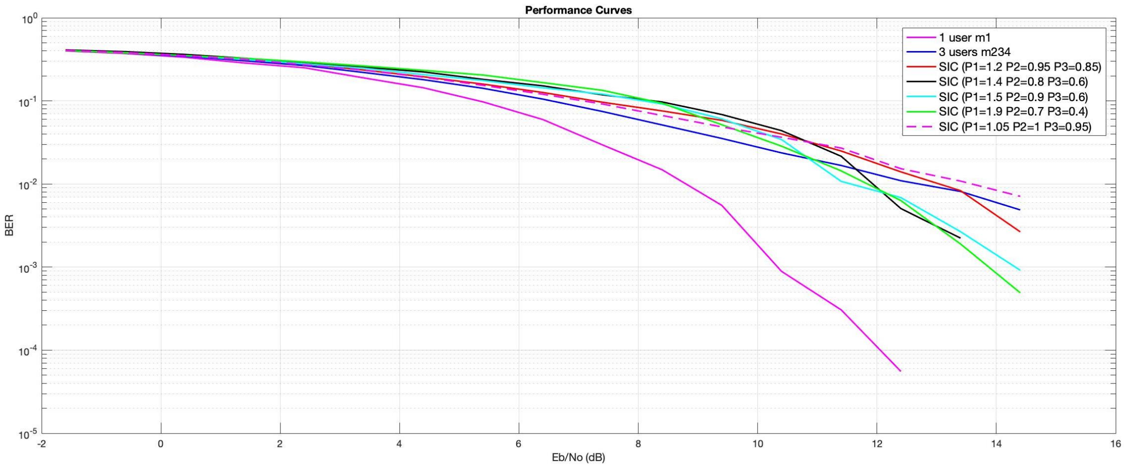

Figure 34: 3 Multi-User with SIC Techniques for different Power Distributions Overall Performance Results

Moreover, these techniques are additionally improving the performance results when under highly heterogeneous distribution of power. In addition, remark that the overall performance is improved when the first user, which has the highest amount of interference due to the noise and the two other users, has an exceedingly high power in comparison with the other two users. This difference in power, allows the first user to improve its individual performance results, which in turn ameliorates the overall performance.

The best results for this scenario applying SIC techniques are obtained , as we can observe in figure 34, for the performance curves under a distribution of $P_1 = 1.9$ and $P_2 = 0.7$ and $P_3 = 0.4$ in green and $P_1 = 1.5$ and $P_2 = 0.9$ and $P_3 = 0.6$ in light blue.

4.3.3 4 Multi-user with SIC Techniques

In this subsection we have created a multiple user scenario, specifically 4 users, while at the receiver implementing SIC techniques. We have defined various power distributions for the four users, in order to accomplish the necessary heterogeneous distribution needed by the SIC techniques to result in a positive performance. Similarly to the previous analysis, are going to compare the results with the simple 4-user scenario without SIC schemes in order to easily appreciate the performance results.

For this scenario we have obtained several performance curves for different signal power distributions in 35.

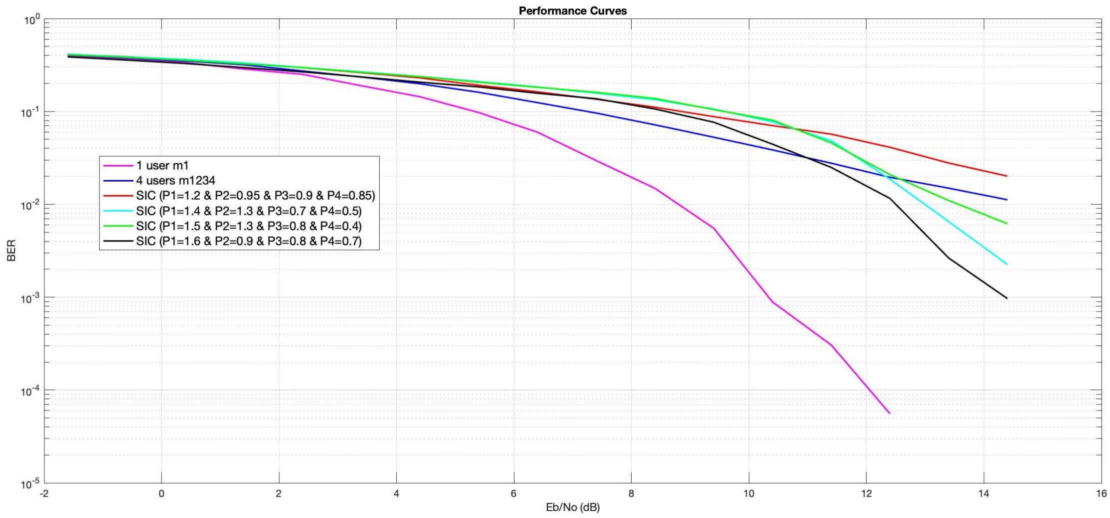

Figure 35: 4 Multi-User with SIC Techniques for different Power Distributions Overall Performance Results

The performance results obtained in this 4-user scenario complies and follows the results for the previous multiple users scenarios implementing SIC techniques in the receiver.

From the previous figure, 35 we can conclude that under favorable signal to noise ratio conditions, high Eb/No, SIC techniques applied in the receiver in addition to heterogeneous power distribution, undoubtedly outperform the performance results of the simple receiver implemented in the standard with homogeneous distribution of power.

Furthermore, in figure 35, we can clearly observe the previously stated conclusion. These techniques overall performance is improved when the first user has a remarkably high power in comparison with the other two users. Moreover, the other users don't require such high power or difference in power between them, as for each one the interference is being lowered, as we are sequentially subtracting the previous decoded users. For this reason, the best performance curve is the black curve, which has a power distribution of $P_1 = 1.6$ and $P_2 = 0.9$ and $P_3 = 0.8$ and $P_4 = 0.9$.

We can conclude, that the overall performance results for the scenario with SIC depends on the scenario conditions and the heterogeneous distribution of power between users.

Convolutional Coding & Viterbi Decoding

5.1 Introduction

As mentioned in the introduction, this study focuses on analyzing the performance results of implementing the IEEE 802.15.4 standard under a multiple user scenario. However, under this type of environment the main limiting performance parameter is the multiple access interference (MAI) or inter-user interference. Therefore, in order to counteract this issue, we have implemented several additional techniques that have been proven effective in other scenarios, in order to analyze the enhancement in performance when introduced into the Standard system.

This standard uses a combination of CSS techniques, DQPSK in addition to an 8-ary bi-orthogonal coding to encode the information. The CSS modulation and demodulation scheme provides coding gain in addition to spreading gain, by offering sub-chirp sequence division as well as frequency division [55]. However, It has been said that the coding scheme implemented in the standard we are analyzing, from a channel coding perspective is not optimal [56]. This is because the sub-optimal coding gain is given by the symbol-to-chirp mapping implemented that can be seen as a block code.

To protect against possible errors during the transmission over a noisy communications channel, error control coding have been found to protect the source digital data. The two main types of error control codes are Block codes and Convolutional codes. Block codes were the earliest type of codes to be investigated, and the encoding only depends on the current message, thus they don't have memory [57].

They are extremely efficient for digital implementations and are specially powerful under scenarios where the channel errors occur in clusters or bursts. However, they have two main drawbacks, soft-decision decoding is difficult to fully implement and code synchronization is hard to achieve.

On the other hand, Convolutional coding depends on the current message as well as the previous one, making it a memory system, which is suitable for applications requiring good performance [58]. Convolutional codes decoders exploit the Viterbi algorithm, which is easily able to take full advantage of soft-decision information thus obtaining a gain of around 2dB over hard-decision. Moreover, code synchronization is easily achieved with convolutional codes [59].

In general error-correction coding enhances the performance of the system. In the following figure 36, we can observe a comparison of the error performance between a typical modulation scheme with and without coding. The coding gain between the uncoded and coded curves can be observed in the reduction of E_b/N_o from 14dB to 9dB while maintaining the same error performance [47].

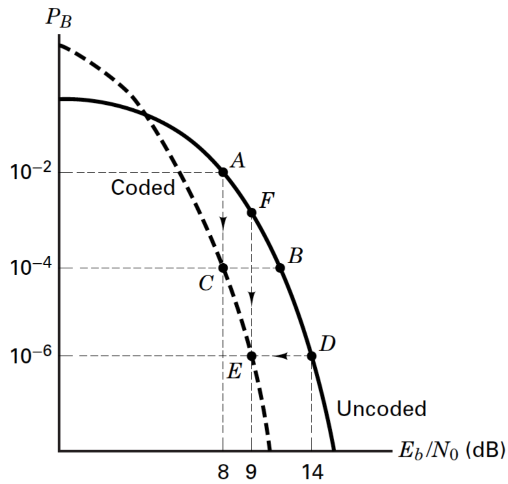

Figure 36: General Comparison Performance between Coded and Uncoded Systems.

For this reason, we propose a new coding scheme with improved coding gain for this standard, which will introduce convolutional codes that have higher coding gains than block codes. Consequently, we will include in this project a coding and decoding block in order to provide robustness to the data transmitted and received, which improve the overall system performance.

Therefore, we will first introduce the theory behind coding and decoding. Afterwards we will explain in detail each of the blocks, plus its implementation into the system. Lastly, we will define and create some new scenarios in which we will include these blocks and test the resulting performance under several environment and conditions. Moreover, as previously done, we will compare the results and give an in depth analysis to understand the results.

5.2 Fundamentals & System Design

In this section we are going to introduce the fundamental theory of convolutional codes in addition to detailing the coding we will implement in our system. Furthermore, once we explain the mechanism to encode the signal, then we will detail the decoder that must be implemented in the receiver in order to obtain the original input data from the received signal, which has been affected by a noisy communications channel.

The basis of the convolutional coding is to generate a continuous output stream of bits from a continuous source, which is why it is used for real-time applications. Convolutional codes have memory, which means that the n-encoding procedure is a function of the k input in addition to being a function of the previous K-1 inputs, thus the memory m=K-1. As a result, a convolutional code is described with 3 integers; the code rate k/n, information per coded bit and the constraint length K, which represents the number of k-stages of the shift register. As a result, the complexity of the code is directly related to the constraint length K [27].

For these types of codes, the decoder is the Viterbi decoding algorithm, which was first discussed in 1967 by Viterbi. The Viterbi algorithm is a maximum-likelihood (ML) sequence decision algorithm. This algorithm performs a maximum likelihood decoding while introducing the special structure of the trellis code for its advantage.

It calculates the minimum Hamming distance between the received signal and all the trellis paths, while moving from left to right through the trellis, allowing the algorithm to discard all the subpaths that could not possible be the prefix of the best path. This early rejection of the unlikely trellis paths allows the decoder to reduce in complexity.

Furthermore, this algorithm has been designed to operate both with hard and soft decisions. In general, Soft decision decoding has a gain in the performance results over the Hard decision. In the following figure 37 we can observe a general comparison between the performance of the same system, without coding, with Hard and Soft decision decoding. As we can perceive there is a gain of around 3dB between hard and soft decision decoding.

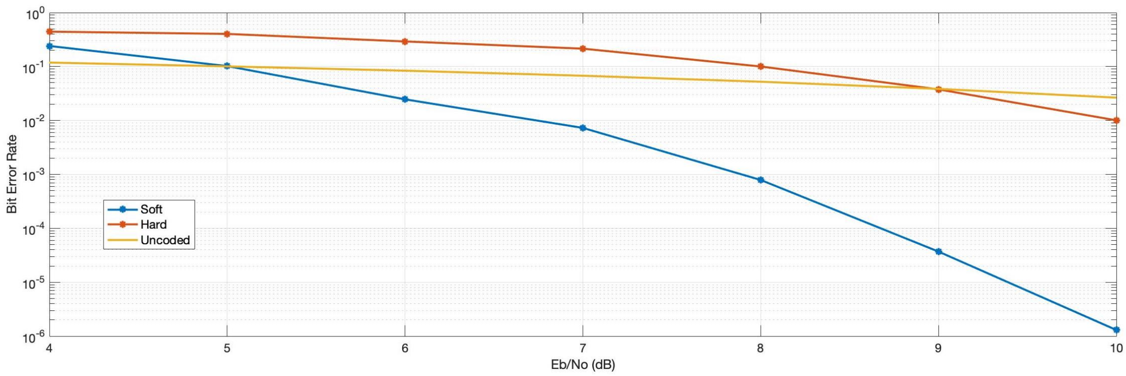

Figure 37: Performance Comparison between Soft and Hard Decision Decoding

Moreover, both coded performances share a similarity at low E_b/N_o, they result in worse performance than the uncoded system. This behaviour is kept indifferently from the system characteristics. This is because when there are several errors the error correction coding and decoding system can not correct all of them and instead replicate those errors all through the data, deteriorating the performance results. However, for more favorable conditions, the coding system is able to start correcting errors thus quickly performing much better than a system without coding. As we can observe the E_b/N_o conditions have to be around 5dB for the Soft coding to perform better than the uncoded system. However, for Hard decoding the conditions are higher at around 9dB.

To sum up, the Viterbi decoding algorithm advances through the trellis path by following the minimum cumulative Hamming distance and eliminating non optimal paths, until there is only one. For further information or detail into this example, please refer to [47, 60].

After understanding the operation of a general convolutional code and the Viterbi algorithm, we are going to introduce the code implemented in our system. We have chosen to implement one of the most common convolutional codes, which has a constraint length equal to 7 and a $rate = 1/2$. This code can be represented by the following diagram and the two linear functions that define this code are the octal numbers 171= binary[1111001] and 133=binary[1011011].

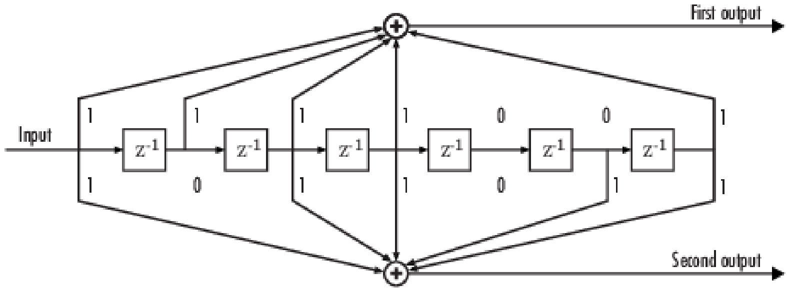

Figure 38: Convolutional Encoder for rate R=1/2 and constraint length K=7

In this diagram we can observe that the convolutional code encoder we are going to implement has a rate=k/n= 1/2, as we have one input and two outputs. In addition this encoder has 6 registers, delays elements noted as z^{-1}. Furthermore, this encoder has a Hamming distance equal to 10, which means that the code can correct 4 errors [47, 59-61].

5.3 Scenarios & Results

In this section we are going to define different scenarios where we will include in the overall system Convolutional Coding and Viterbi Decoding, in order to evaluate and analyse their performance. Moreover, an in depth analysis on the results will be conducted for each single case. In addition, a comparison between scenarios will also be executed to examine and evaluate their differences and similarities.

There are 2 basic scenarios we can define using the previously mentioned techniques; standard friendly and non standard friendly. First of all, we are going to design a system that incorporates the standard we are evaluating in this thesis, IEEE 802.15.4, in addition to these coding and decoding techniques used to enhance the overall system performance. Consequently, this new scheme results in a Standard friendly implementation.

Second of all, we will discard a part of the transmission and reception scheme as defined in the standard and propose a new system, designed to enhance performance results. Consequently, as we are modifying the standard, this scenario will be not standard friendly.

Furthermore, both new systems designs will be analyzed under a single user and a multi-user scenario, similarly to the previous analysis, in order to compare the performance results.

5.3.1 Standard Friendly

As we previously mentioned, this scenario incorporates both the Standard system in its entirety in addition to adding Convolutional coding and Viterbi decoding. Consequently, the coding and decoding blocks will be set at the very beginning and end of the overall system, as we can appreciate in the following figure 39.

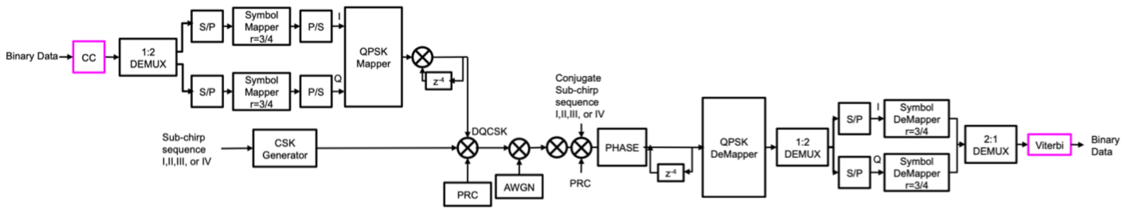

Figure 39: Standard, CC and Viterbi Complete Block System

As we can see in the previous figure, the standard scheme has not been modified, however we have incorporated the coding and decoding blocks in the extremities of the design in order to provide robustness to the data. The Viterbi decoding, as explained in the fundamentals section, can be either a Hard decision or Soft decision decoding.

Consequently, the Viterbi decoding scheme will be a Hard Decision Decoding, as we are implementing it at the end of the system, once the standard has already decoded the data. This has to be taken into consideration when analyzing the performance results, as Hard decision decoding doesn't offer the same level of performance enhancement as with Soft Decision Decoding, as previously shown.

Furthermore, even though the system has been minimally modified, the convolutional coding scheme implemented will impact on the overall performance of the system. The main parameter affected will be the rate of the overall system, which in turn will impact on the statistics of the AWGN channel.

As detailed in the description of the Standard in Chapter 3, the rate the system is $rate = 3/4$ as introduced by the Symbol Mapping block. However, the convolutional code we are going to implement in this scenario has a rate of $rate = 1/2$. Consequently, the overall system will have the product of both, $rate = 1/2 * 3/4 = 3/8$.

We are defining all scenarios under the same general conditions to be able to compare the performance results. For this reason, the modification of the overall rate impacts in the calculation of the statistics of the AWGN noise. The following equations define the calculations performed to simulate the channel noise.

$$variance = P_s/(Eb/No * rate * b * L) \tag{5.1}$$

$$sigma = sqrt(variance/2) \tag{5.2}$$

$$noise = sigma(px) * (randn(N) + j. * randn(N)) \tag{5.3}$$

As we can observe, if we decrease the rate from 3/4, standard only, to 3/8 with this new design, the variance is doubling and thus we have an increase in the overall noise, which will affect negatively in the overall performance.

5.3.1.1 Single User Scenario

Following the general structure, we first include the results of the overall performance of this new Standard Friendly system under a single user scenario in figure 40. As we can observe the performance has been greatly affected and deteriorated by implementing this Hard decision coding and decoding blocks.

Following the theory explained previously, we can reason that the performance for unfavorable conditions, low E_b/N_o, concurs with the expected results. However, we would expect that the coding performance at high E_b/N_o conditions outperformed the simple standard, which is not the results we obtain. The gain expected from including coding into our system has been obfuscated by the deterioration of the overall rate, which increases the channel noise and thus the errors found in the received data.

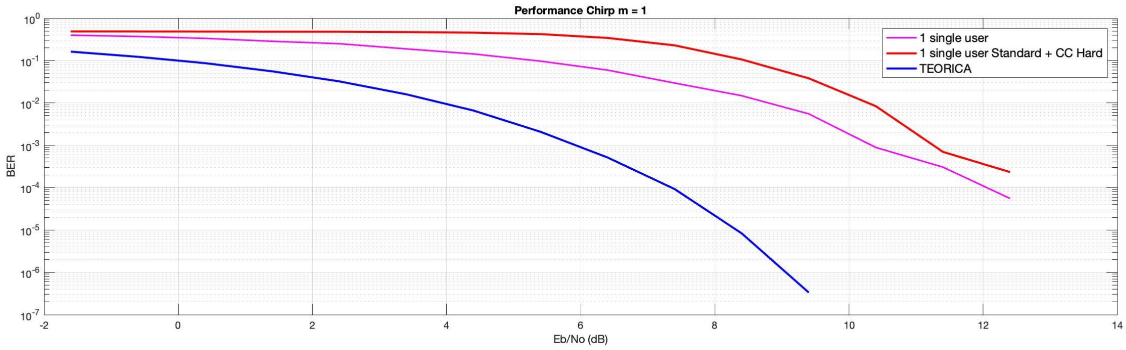

Figure 40: Single User Standard Friendly Performance Results

5.3.1.2 Multi-User Scenario

Following the previous results, we are going to analyze the same system under a multi-user scenario, specifically 2 users employing the Chirp sequences m=1&2 and m=1&3, to observe the performance under different levels of interference.

From these results we can observe the same behaviour for the 2 user scenario than for the single one. The resulting performance is deteriorated due to the decreased rate, which overpasses the coding gain of the extra coding blocks.

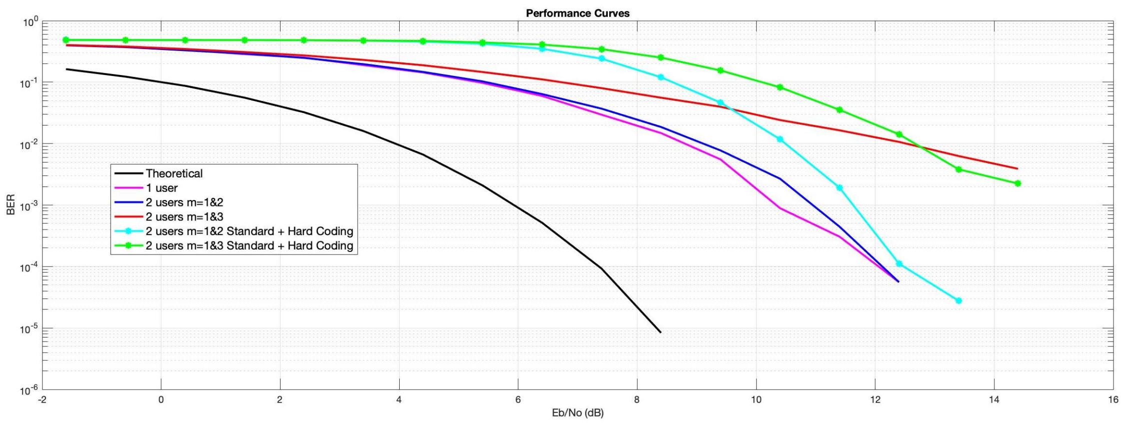

Figure 41: 2 Multi-User Standard Friendly Performance Results

However, we must point out that for the most interfered system m=1&3, as the two chirp sequences are not as orthogonal, thus increasing overlaps, around $E_b/N_o = 13dB$ the coding gain surpasses the deterioration of the noise, resulting in an enhanced performance compared to the same scenario without coding. Consequently, it seems that these coding techniques are enhancing the performance when the system is under high interference.

For this reason we are going to extract results for this system under a 3 and 4 multi-user scenario, which have high interferences. In the following figure 42 we can observe the performance results for all single and multi-user scenarios for the standard with the addition of the coding blocks and without them.

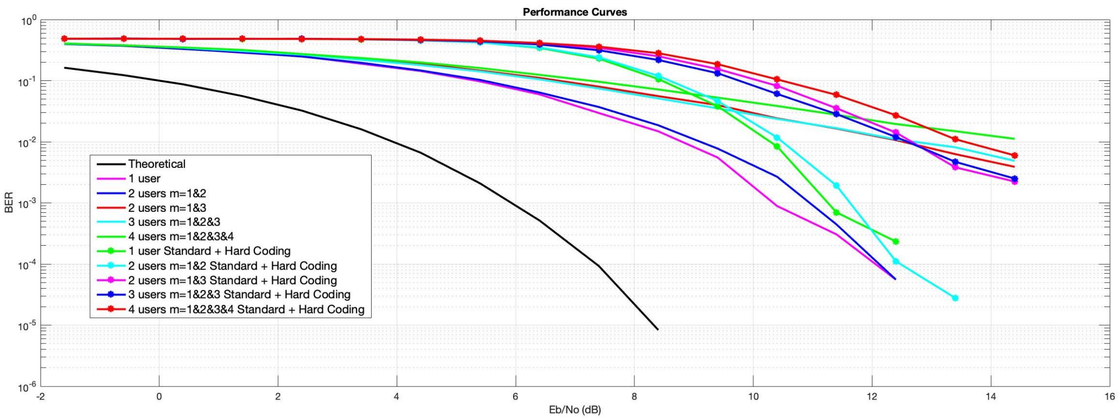

Figure 42: Multi-User Standard Friendly Performance Results

In the previous figure, we can observe that under all scenarios the performance behaviour concurs with the theoretical findings.

At low E_b/N_o conditions the performance results are better for those systems without any additional coding. This is because under these conditions the coding and decoding blocks are not able to correct the errors and due to their definition they spread and duplicate these errors, which further deteriorates the performance results. However, when the system is under favorable conditions, these coding blocks are able to not only detect but correct errors making the performance results quickly improve. This last behaviour can be seen for the most interference ridden scenarios, 2 (m=1&3), 3 and 4 multi-users, for very high E_b/N_o conditions, at around 13dB.

However, we must note that the improvement of performance is limited due to the decreased rate, thus increased noise factor, of the overall system in addition to employing Hard decision decoding, instead of Soft decision. For this reason, in the next subsection we have modified the system to decrease the noise, by increasing this rate, and apply Soft decision decoding, to analyse the maximum possible improvement under these scenarios.

5.3.2 Non Standard Friendly

In this section we are going to define a new system, which is not standard friendly, as we are going to discard a part of the transmission and reception scheme while implementing convolutional coding and Viterbi decoding.

From the standard we are going to eliminate the symbol mapping block from transmission and reception, as it is restricting and reducing the overall performance. Similarly to the previous scenario, we are going to include the Convolutional coding and Viterbi coding at the very beginning and end of the scheme. The overall system for this scenario is shown in the following figure:

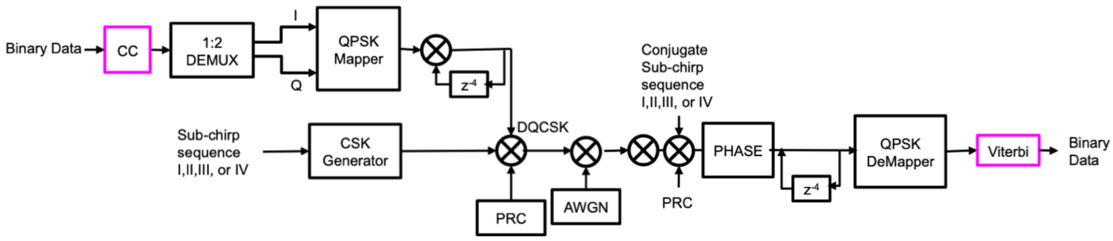

Figure 43: Non Standard Friendly Block System

As we can observe in the block system diagram, we have eliminated the Symbol Mapping block from transmission and reception. Eliminating this block allows us to implement a Viterbi Soft Decision Decoding. As previously mentioned, Soft decision decoding yields better performance results than hard decoding, thus we expect this system to perform similarly or better than the Standard friendly system.

Moreover, eliminating this block also allows us to increase the overall system rate. The Symbol Mapping was introducing a rate=3/4 which in addition to the convolutional coding rate of 1/2, resulted in an overall rate of 3/8. As previously explained the rate decreasing by half influenced in increasing the noise of the channel and thus affecting negatively in the resulting system performance.

Consequently, in this new scenario, we have eliminated this block, which results in an overall system rate of 1/2 from the Convolutional coding block. As a result, this new rate is lower than the Standard system without additional blocks but higher than the Standard friendly proposed solution, which reduces the channel noise in comparison following the same calculations as previously.

5.3.2.1 Single User Scenario

Following the general structure, we first show the results of the overall performance of this new Non-Standard Friendly system under a single user scenario in figure 44. As we can observe the performance has been greatly improved by implementing this Soft decision coding and decoding blocks while excluding the intrinsic 3/4 symbol mapper of the standard.

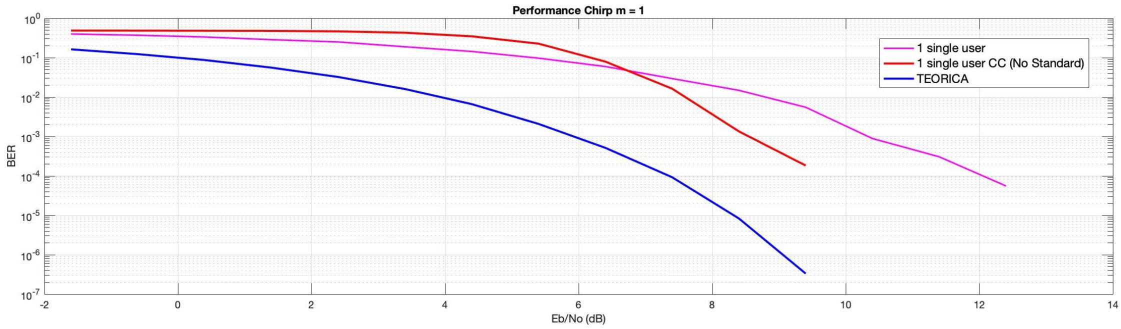

Figure 44: Single User Non-Standard Friendly Performance Results

Following the theory explained previously, we can reason that the performance for unfavorable conditions, low E_b/N_o, concurs with the expected results. At low E_b/N_o conditions the performance results are better for the standard system without any additional coding. This is because under these conditions the coding and decoding blocks are not able to correct the errors and due to their intrinsic properties. In addition they spread and duplicate these errors, which further deteriorates the performance results.

However, when the system is under favorable conditions, these coding blocks are able to not only detect but correct errors making the performance results quickly improve. At high E_b/N_o conditions, around 7dB, these coding techniques outperform the simple standard.

We must remark that the E_b/N_o threshold for the coding techniques to outperform the regular system is much lower for the Soft Decision coding than for the Hard decision coding, as seen in the theory. Thus our results concur and follow the theoretical behaviour of coding and decoding techniques.

5.3.2.2 Multi-User Scenario

Following the previous results, we are going to analyze the same system under a multi-user scenario, specifically 2 users employing the Chirp sequences m=1&2 and m=1&3, to observe the performance under different levels of interference.

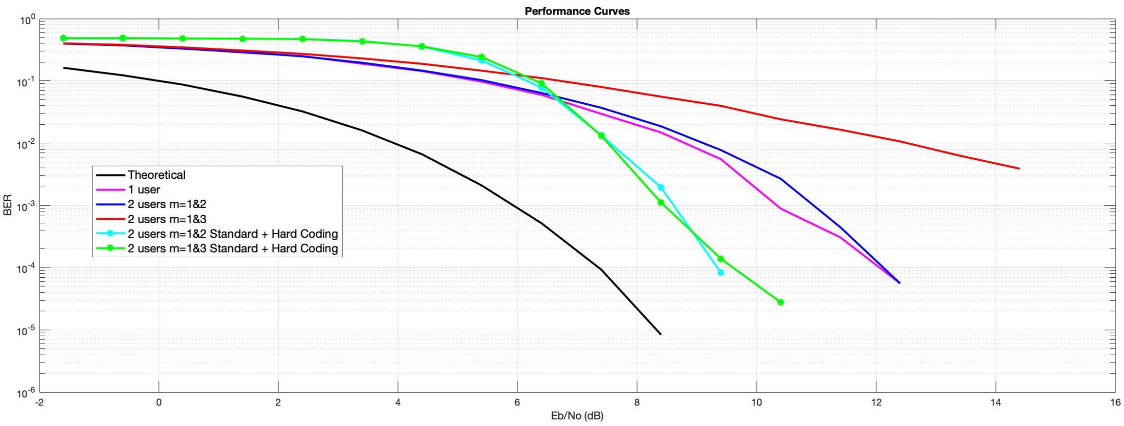

Figure 45: 2 Multi-User Non-Standard Friendly Performance Results

From the previous results we can observe the same behaviour for the 2 user scenario than for the single one. The resulting performance is extremely improved with the inclusion of the Soft coding techniques in addition to the removal of the symbol mapper from the standard. Moreover, we can remark that the performance of this system is not determined not deteriorated by the slight increase in interference when comparing the curves for the m=1&2 and m=1&3 scenario. Both results follow the same theoretical behaviour and minimally differ in the threshold E_b/N_o which is around 6dB.

Furthermore, we have extracted the performance results for this system under a 3 and 4 multi-user scenario, which have higher interferences, to analyze the behaviour of this system in relation to the interference factor. In the following figure 46 we can observe the performance results for all single and multi-user scenarios for this new non-standard friendly system, were we have included convolutional coding and Viterbi soft decision decoding while extracting the 3/4 symbol mapper intrinsic to the standard.

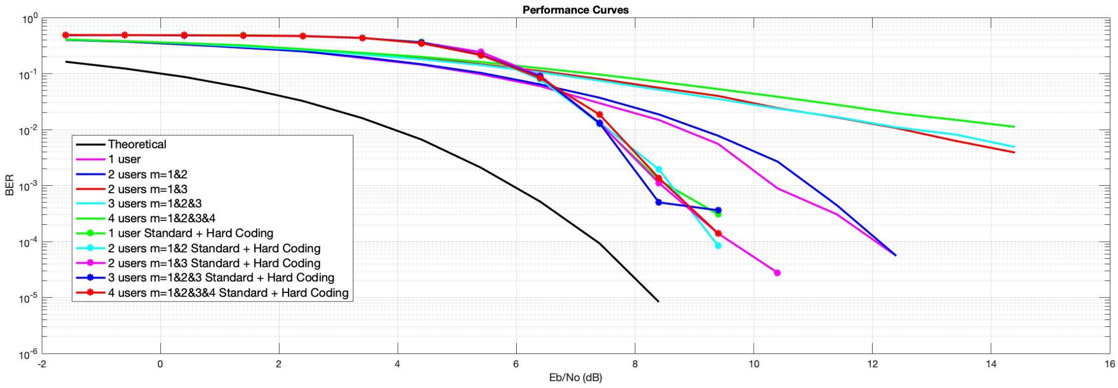

Figure 46: Multi-User Standard Friendly Performance Results

In the previous figure, we can observe that under all scenarios the performance behaviour concurs with the theoretical findings. At low E_b/N_o conditions the performance results are slightly better for those systems without any additional coding, for the same reasoning. Under these conditions the coding and decoding blocks not only are not able to correct the errors but they duplicate them all through the system, further deteriorating the performance results, which is why we obtain worse results. However, when the system is under favorable conditions, these coding blocks are able to not only detect but correct errors making the performance results extremely fast outperform the simple system.

Furthermore, we can conclude that the performance results for these scenarios are completely independent from the interferences in the scenarios, as we have obtained extremely similar results for the single and multiple user scenarios.

Moreover, as in the theoretical explanation, the E_b/N_o threshold, from where the coding techniques start outperforming the simple system, is much lower for the Soft Decision decoding than for the Hard decision. If we go to the previous scenario, we found this threshold to be around 13dB. For the Soft decision we now have obtained this threshold to be around 6dB. This improvement, is not only related to the theoretical gain between the Hard and Soft decision decoders, but due to the overall system rate. This rate is clearly affecting the performance results for both scenarios and thus must be taken into consideration not only when analyzing results but prior, when designing possible systems solutions.

Conclusions

The aim of this project was to evaluate the performance of the IEEE 802.15.4 standard under different channel scenarios. Moreover, we evaluated the difference in performance when applying SIC techniques in the system with the objective of enhancing the results. Furthermore, we created two scenarios including Convolutional coding and Viterbi decoding techniques into our implemented system, both with different levels of modifications, in order to analyze the performance results. As a result we have defined, created and obtained performance results for the several different single user and multi-user scenarios, some Standard friendly and some non-standard friendly.

IEEE 802.15.4 Standard

First of all, in this thesis the IEEE 802.15.4 Standard has been thoroughly studied. Due to the amount of different physical channels defined in the standard, a state of the art and a study into each technique has been conducted, in order to be able to select one. The implementation of this standard has been based on the physical channel modelled for Chirp Spread Spectrum (CSS) as described in the standard. Afterwards, we created different scenarios,single user and multi-user schemes under different conditions, for which we evaluated the performance, as shown in the following figure .

When comparing the single user performance results from the Standard to the theoretical curve, we can observe some differences which are mainly due to to factors, noise and the defined Standard transmission and reception system. First, we are introducing white Gaussian noise (AWGN) in the system, which is reducing the performance, in comparison to the theoretical results.

Second, the definition of the IEEE 802.15.4 CSS standard is introducing several aspects, which causes a reduction and deterioration in performance results.

The standard defines a system in which Chirp sequences are used in turn with different time gaps, during which no signal is being sent thus causing efficiency losses and as a result the performance deteriorates in comparison to a full continuous signal. Moreover, the signal is windowed by a cosine pulse (PRC) to lower the effect of the frequency jumps, which in turn further includes efficiency losses in the signal.

Furthermore, the standard defines a transmission and reception system where it includes a differential filter that is deteriorating the performance. This filter is propagating and duplicating the original errors of the received signal. Worst-case scenario being that all the errors are duplicated and are not correctly decoded, causing a reduction by around -3dB.

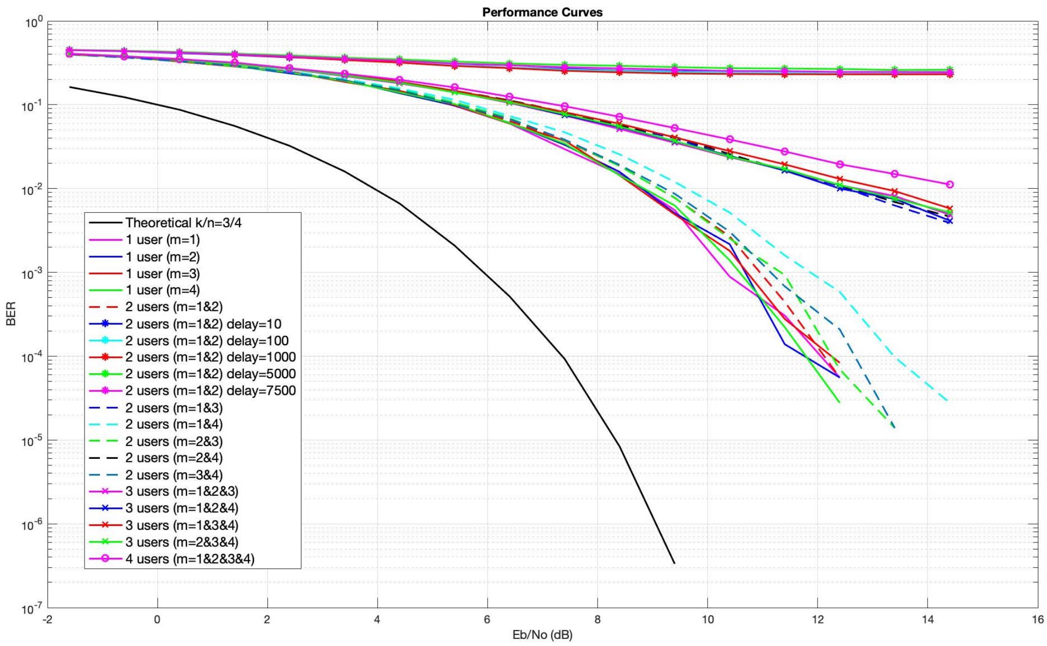

Figure 47: Standard Under Multiple Single and Multiple-User Scenarios Performance Results

When comparing the standard curves between single and multi-user scenarios we can observe how the main reduction factor in performance is the non-orthogonality of the chirp sequences, thus creating interferences between them. We have detailed the pair combinations of chirps to analyze the interferences and thus overlaps between them. We have seen that the worst interfering combinations are the pairs combination 1&3 and 2&4, which share frequency sub-bands with opposite slopes, thus overlapping. For this reason, those both performance curves obtain the worst results.

Furthermore, reviewing the results for the 3 and 4 multi-user scenarios, we can conclude that the previous pairs combinations dominate the degradation of the overall performance, which is why the results have minimal variation and deterioration when introducing 1 or 2 extra users into the system where one of these combinations pre-exists.

Lastly, reviewing the results obtained for the scenarios with different starting times between the pairs of chirp sequences, we can conclude that this standard requires some type of synchronization control under a multi-user scenario in order to yield acceptable performance results.

Standard and SIC Techniques

Second of all, we have studied and implemented into our Standard system the novel Successive Interference Cancellation Techniques to evaluate the enhancement in performance.

In figure 48 we can observe the performance results for the Standard system including SIC Techniques at the receiver under single and multi-user scenarios.

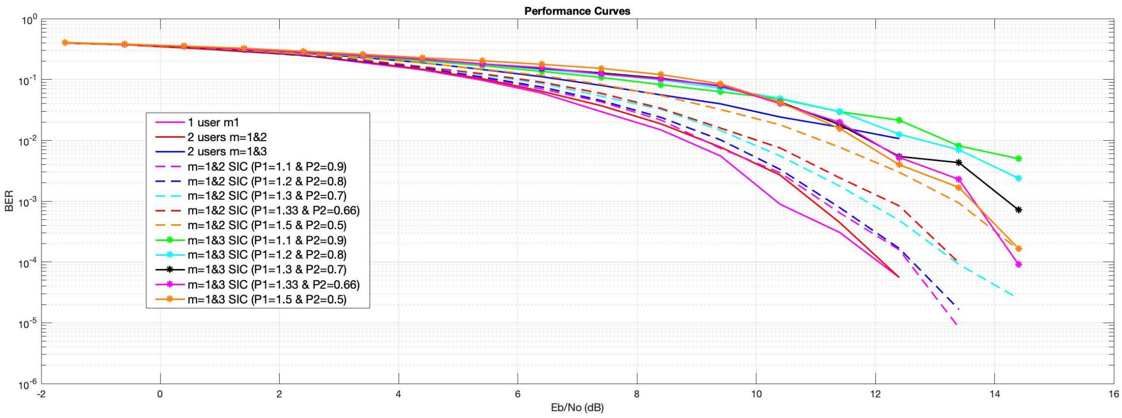

Figure 48: Standard with SIC Techniques Under Multiple Single and 2 Multi-User Scenarios Performance Results

From the previous figure we can conclude that at low signal to noise ratios, low Eb/No, under a 2 multi-user scenario the simple receiver defined for the standard without differences in power distributions is outperforming the performance of the receiver with SIC techniques and heterogeneous distribution of power.

As we can appreciate from the figure, the application of SIC schemes in the receiver in a 2-user scenario obtains different results depending on the combination of the chirp sequences, 1&2 or 1&3 as their orthogonality is different. We can observe that for a system under small interferences, thus the chirp sequences are almost perfectly orthogonal as it is the case for m= 1&2, the SIC techniques are not outperforming the simple standard system results. Additionally the heterogeneous distribution of power is negatively affecting the performance results of this scheme.

However, this system under a higher amount of interference, as it is the case for m= 1&3, the SIC techniques do improve the performance results under favorable conditions, high Eb/No. Moreover, these techniques are additionally enhancing the performance results when under highly heterogeneous distribution of power.

Therefore, we can conclude that the SIC Techniques are highly valuable and efficient under high interference scenarios as they enhance the overall performance results for the system. Moreover, the best results for this scenario applying SIC techniques are obtained when under highly heterogeneous scenarios.

Moreover, after obtaining these results, we analyzed the performance of this system with SIC techniques under further interferences scenarios, as it is the 3 and 4 multi-user scenario.

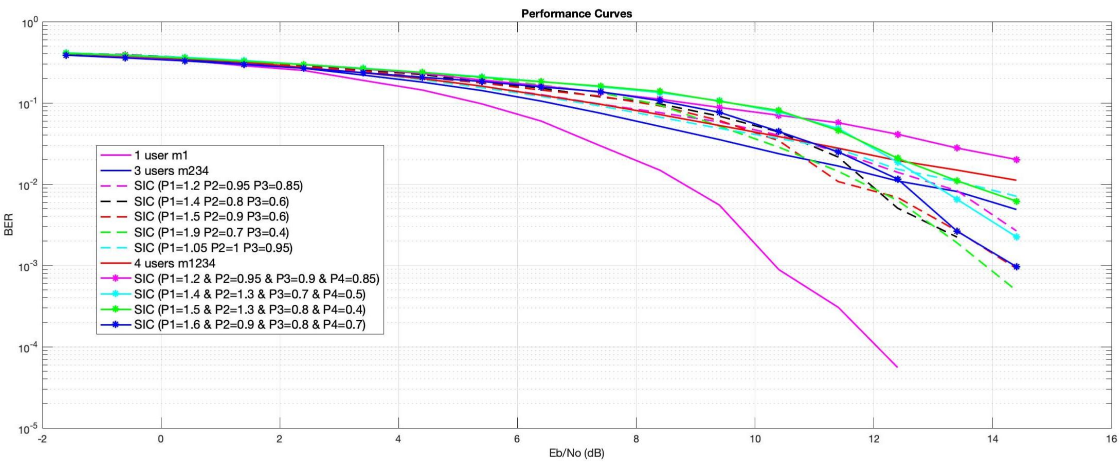

Figure 49: Standard with SIC Techniques Under 3&4 Multi-User Scenarios Performance Results

These performance results comply and follow the results for the previous 2 multiple users scenarios implementing SIC techniques in the receiver.

At low signal to noise ratios, low Eb/No, both systems, with and without SIC, obtain similar results. For intermediate conditions, and under this specific scenario, the system designed for the standard is outperforming all the other results. However, under favorable signal to noise ratio conditions, high Eb/No, SIC techniques undoubtedly outperform the performance results of the simple system designed for the standard.

Moreover, SIC techniques are additionally improving the performance results when under highly heterogeneous distribution of power. These techniques overall performance is improved when the first user has a remarkably high power in comparison with the other two users. Moreover, the other users don't require such high power or difference in power between them, as for each one the interference is being lowered, as we are sequentially subtracting the previous decoded users.

We can conclude, that the overall performance results for the scenario with SIC depends on the amount of interference, the scenario conditions and the heterogeneous distribution of power between users.

Convolutional Coding and Viterbi Decoding

Third and last of all, we have studied in depth coding and decoding techniques, specially Convolutional codes and Viterbi decoding. In this part, we defined two different scenarios, one standard friendly, for which we didn't modify the already implemented system. In addition, another scenario non-standard friendly, which consisted of excluding some parts of the standard and implementing coding and decoding blocks.

For the Standard Friendly solution, we have applied a convolutional coding block at the beginning of the system and a Viterbi with Hard decision decoding block at the very end. For this new system we have obtained the results similarly to all the previous analysis, for single and multi-user scenarios, which can be found in the figure 50.

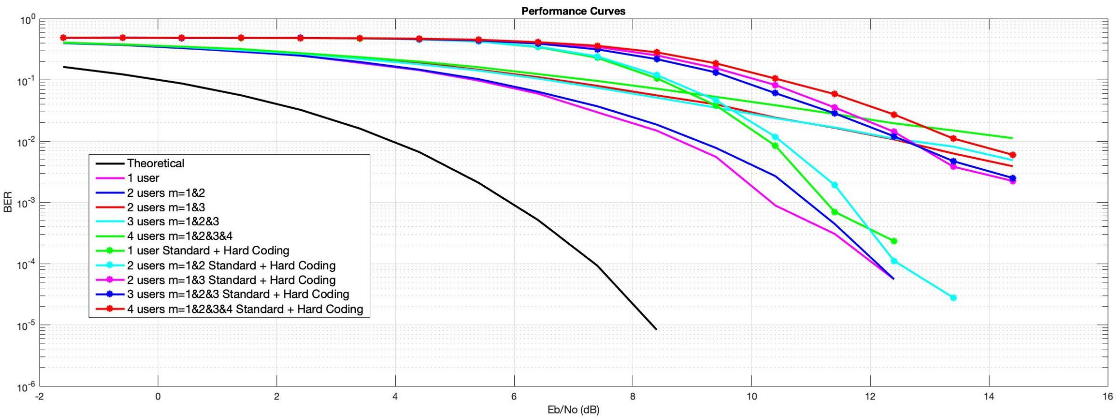

Figure 50: Standard with SIC Techniques Under 3&4 Multi-User Scenarios Performance Results

In the previous figure, we can observe that under all scenarios the performance behaviour concurs with the theoretical findings. At low E_b/N_o conditions the performance results are better for those systems without any additional coding. This is because under these conditions the coding and decoding blocks are not able to correct the errors and due to their definition they spread and duplicate these errors, which further deteriorates the performance results.

For this system unexpected results were obtained at high E_b/N_o conditions, as we expected the new systems results to exceedingly outperform the simple standard. However, it is not so, because the gain expected from including coding into our system has been obfuscated by the deterioration of the overall rate, which has been decreased by half, causing an increase on the channel noise and thus the errors found in the received data.

However, for highly interference ridden scenarios, such as 2 users m=1&3, 3 and 4 multiple-users scenarios, some improvement can be seen at around $E_b/N_o = 13dB$, where the coding gain surpasses the deterioration of the noise, resulting in an enhanced performance compared to the same scenario without coding. Consequently, it seems that these coding techniques are enhancing the performance when the system is under high interference.

Nonetheless, this improvement is limited due to the lower rate of the overall system in addition to employing Hard decision decoding, instead of Soft decision.

For this reason, a System with a Soft decision decoding scheme has been defined and analyzed. This new system is not standard friendly, as we are going to discard a part of the transmission and reception scheme, the symbol mapper, while implementing convolutional coding and Viterbi decoding.

Eliminating the symbol mapper allows us to implement a Viterbi Soft Decision Decoding, thus expecting this system to perform similarly or better than the Standard friendly system as Soft decision decoding yields better performance results than hard decoding in theory.

Moreover, eliminating this block also allows us to slightly increase the rate to $1/2$. As previously explained the decreasing of the rate also influenced in increasing the noise of the channel and thus affecting negatively in the resulting system performance.

In figure 51 we show the obtained results of analyzing this new system under several scenarios. As we can observe the performance has been greatly improved by implementing this Soft decision coding and decoding blocks while excluding the intrinsic $3/4$ symbol mapper of the standard.

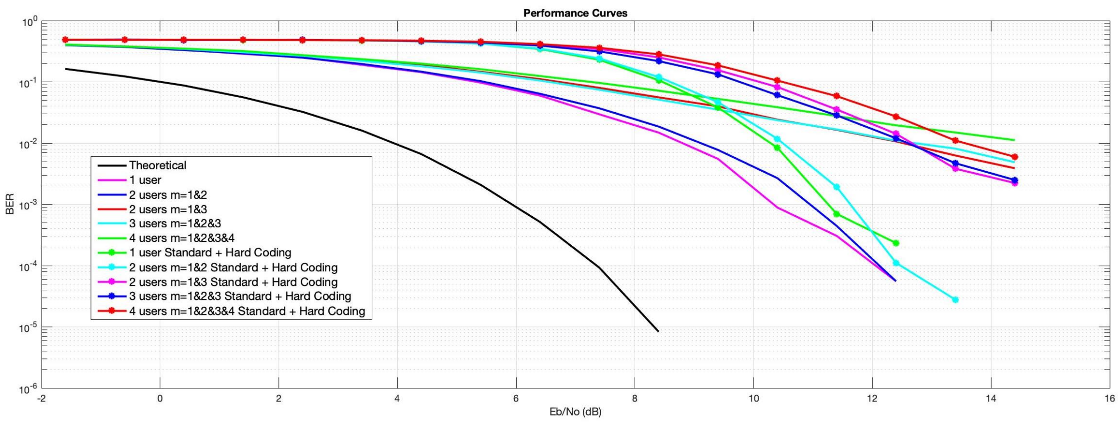

Figure 51: Standard with SIC Techniques Under 3&4 Multi-User Scenarios Performance Results

In the previous figure, we can observe that under all scenarios the performance behaviour concurs with the theoretical findings. At low E_b/N_o conditions the performance results are slightly better for those systems without any additional coding, for the same reasoning.

Under these conditions the coding and decoding blocks not only are not able to correct the errors but they duplicate them all through the system, further deteriorating the performance results, which is why we obtain worse results.

However, when the system is under favorable conditions, these coding blocks are able to not only detect but correct errors making the performance results extremely fast outperform the simple system. Furthermore, we can conclude that the performance results for these scenarios are completely independent from the interferences in the scenarios, as we have obtained extremely similar results for the single and multiple user scenarios.

Moreover, as in the theoretical explanation, the E_b/N_o threshold, from where the coding techniques start outperforming the simple system, is much lower for the Soft Decision decoding than for the Hard decision. For the Standard friendly system, Hard decision decoding, this threshold is around 13dB, where for the Soft decision we can observe how it is around 6dB.

6.1 Future Development

We have just summarized the analysis and conclusions performed throughout this thesis regarding each and every different scenario we created. In addition, we propose several further development and future investigation paths in line with this project.

First of all, the standard we have chosen to implement has several physical layer options which have been disregarded in this thesis at the very beginning, as we have chosen to only analyse one of the options. For this reason, to further investigate the performance of this standard it would be necessary to analyze each and every physical layer option procured by this standard.

Furthermore, in this thesis we have focused on the analysis of the physical layer dismissing the MAC layer proposed in the standard. Thus, an in depth analysis in the complete implementation of the standard, without the exclusion of any part, would be interesting to accomplish.

Moreover, in this thesis we have created a non-standard friendly system, that slightly modified the standard implementation in order to improve the performance results. Thus this path could continue, replacing and further modifying the standard components that are deteriorating the resulting performance.

Last of all, to further research into LPWA networks, M2M communications and the IoT paradigm, other proprietary technologies and standard exists in the market that may obtain greater performance results under multi-user scenarios than the standard we have employed. Thus, another research path is to further investigate into other standards and their performance under multiple user scenarios, from both a physical and mac layer perspective.

Budget

To be able to estimate the budget for this thesis we have to take into account the number of hours dedicated to the thesis, during a period of 5 months, which have to be evaluated at a cost of approximately an engineer.

Moreover, we have to take into consideration all the devices and software needed and thus used to carry out this thesis. No prototype or physical device has been developed for this project. Nonetheless, a computer and a Matlab software licensed has been required.

- Software Costs:

Tool	**Cost (€)**
Computer	1.000
Matlab Student Edition License	35
TOTAL	1.035 €

- Development Costs:

The assigned development cost of a trainee engineer is 9€/h.

Tool	**Hours (h)**	**Cost (€)**
Theoretical Research	180	1.620
Software development	450	4.050
Tests and Analysis	250	2.250
TOTAL	880	7.920 €

Total cost for the thesis: **8.955 €**

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